Supercavitating Propellers

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"At about the same time (1955 г.) I first learned of the work of a Soviet scientist Pozdunin on cavitating propulsors, and also of the Russian term "supercavitation", and then on I began using this way of distinguishing cavitating flows with long trailing cavities from the other cavitating flows. At the beginning there were objections to use of this word, some preferred "developed cavitation", but soon the words "supercavitation" and "supercavitating" came into general use in the U.S.A. and worldwide."

M.P. Tulin, 2000 [1]

1. Summary

The lecture covers the main stages of the development of the research in the field of supercavitating propellers (SCP) both experimental and theoretical. However, it should be viewed only as an introduction to this vast domain attempting to mainly give a notion of the relevant Russian research started in 1941 on the initiative of the academician V.L.Posdunin.

2. Historical notes and experimental investigation

2.1. Test equipment

The cavitation on a model of a screw propeller of just two inches in diameter was first observed by Sir Charles Parsons in 1894 during the tests of a model of the screw propeller of the steam turbine driven "*Turbinia*" (45-ton) in a small water tunnel invented by the researcher for this particular purpose [2]. In 1910 Sir Charles Parsons built the first cavitation tunnel of almost today's dimensions, where one could test the propeller models of a diameter of up 12 inches (304.8 mm). The first cavitation tunnel in Russia was launched in 1933. The first systematic tests of a series of the cavitating propellers with a segment-type sections were conducted by H.W.Lerbs in 1936 with use of the cavitation tunnel built specially for this purpose.

The principle of functioning of the cavitation tunnel, which represents a vertically mounted hermetically sealed variable-diameter tube, is extremely simple (Fig. 1). This experimental installation enables to conduct the force measurement and visual observations of models of the cavitating or

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supercavitating screw propeller for given magnitudes of advance coefficient and axial cavitation number, which are taken equal to those of the full-size propellers for a regime under consideration. Therewith, it is assumed somewhat approximately that such modeling ensures similarity of the cavitation phenomena in the case of a sufficiently developed partial cavitation and in the case of supercavitation, which depend to a lesser degree on the vertical distribution of the hydrostatic pressure, viscosity, turbulence, air content and other factors not taken account of. Note that some of the forms of cavitation are either poorly modeled in cavitation tunnel, or require application of the special procedures for recalculation of the model results to those in full-scale. Examples include cavitation of the tip and axial vortices. Large difficulties occur when modeling of erosion, noise and vibration of the cavitating propeller.

Nonetheless, the most important factors (criteria) during in testing of the supercavitating propellers in the cavitation tunnel are the advance coefficient

$$J = V/(nD) \tag{1}$$

and axial cavitation number

$$\chi = (p_0 - p_v)/(0.5\rho V^2), \tag{2}$$

where p_0 - is hydrostatic pressure at the level of the SCP axis; p_v - pressure of saturated vapor of the fluid at the temperature of the testing, sometimes this value is taken to be equal the pressure of the vapor-fluid mixture in the cavity or the pressure above the free surface of the fluid for the case of superventilation of the cavity under consideration; ρ - fluid density; V- flow velocity in the working section of the cavitation tunnel; n – frequency of rotation; D – diameter of the SCP model.

Local cavitation number σ for cylindrical section of the blade, characterized by the radius r, differs form the axial cavitation number (2) in that in the denominator of the corresponding formula one finds a transport velocity of the blade points, belonging to the given cylindrical section V_E and a hydrostatic pressure is assumed to correspond to the level of the considered point of the corresponding blade section for its certain angular position $p_{or\theta}$, namely

$$\sigma = (p_{0r\theta} - p_v)/(0.5\rho V_E^2) \tag{3}$$

where $V_E^2 = V^2 + (2\pi nr)^2$.

It is obvious, that in the gravity field, when the screw propellers is rotating around a horizontal axis, the local cavitation number is variable for the given point of the considered section, varying during one revolution from a minimal magnitude (in the upper position of the considered point for its motion along a circular trajectory of a given radius) up to a maximal magnitude at a given radius (in the lower position of the considered point).

To control advance coefficient one can employ the velocity of the incoming flow in the working section of the cavitation tunnel (the latter can be varied, by changing the frequency of the axial pump mounted in the tunnel) or the frequency of rotation of the screw propeller model.

To adjust the axial cavitation number one can use a device with a vacuum pump, which enables to pump air out of the volume above the free surface of the fluid, in a special shaft located higher than the working section, i.e. where there is the only place with a free surface (other elements of the cavitation tunnel are hermetically sealed and completely filled with water). The pressure above the free surface in the aforementioned shaft decreases to a certain level, down to a certain value close to zero, which leads to a corresponding reduction of the magnitude of p_0, differing from the pressure above the free surface in a special shaft by the magnitude of the hydrostatic height of the fluid column under propeller model axis.

For proper modeling of the hydrostatic pressure distribution in height, or, speaking more exactly, to secure equality of the local cavitation numbers of the full size propeller and the model in all blade sections with account of gravity, it is necessary to additionally fulfill the equality of the Froude numbers for the model and full-size screw propeller. Absolute error in the determination of the local cavitation number, calculated with use on transfer velocity for the cylindrical blade section at a relative radius $\overline{r}$ (in its upper position), occurring due to disregard of the inequality of Froude numbers, can be found through an almost obvious formula

$$\Delta\sigma = \{1/(n^2 D) - 1/[(n^*)^2 D^*]\}\, \bar{r}g \,/\, [J^2 + (\pi\bar{r})^2], \tag{3a}$$

where n^* and D^* - are the frequency of rotation and the diameter of the full-size screw propeller.

It is seen, that, accounting besides the equality of Froude numbers for another necessary requirement of the identity of advance coefficient for the model and full-size propeller, the aforementioned error can be reduced to zero if, first, the velocity in the working section of the cavitation tunnel would be $\sqrt{M}$ times less that the speed of the motion of the full-size propeller, and, secondly, the frequency of rotation of the model would be $\sqrt{M}$ times more than that of the full-size propeller, where M is the model scale, i.e. equal to the ratio of the diameter of the full-size propeller to that of the model propeller.

For example, if the speed of the full-size propeller equals 60 knots (30.87m/c), diameter 1.054 m., frequency of rotation is 1465 rpm (24.42 revolutions a second), then, for the simultaneous fulfillment of the identities of the Froude numbers and advance coefficient it is necessary to ensure the speed of 13.45 m/s in the working section and the frequency of rotation of 3363 rpm (56.05 revolutions a second) when testing in the cavitation tunnel a supercavitating propeller model of diameter 0.2 m. Note, that the results obtained for the model can, in principle, be realized for good experimental installations. But more often during the tests there are used smaller speed and frequency of rotation, which is acceptable only in those cases, when the arising error, in accordance with (3a), does not exceed reasonable limits narrowing with the reduction of the axial, and, correspondingly, local cavitation numbers.

The influence of the walls of the cavitation tunnel represents an obstacle for a proper modeling, because there are no such walls in the full-size situation. The effect of the walls of the cavitation tunnel may become unacceptably large especially when investigating the supercavitating regime, for which the flow blockage in the tunnel working section due to development of large cavities can noticeably influence the experimental results. Besides, the influence of the free surface (i.e. phenomena of ventilation and wave making) is as a matter of principle impossible to study in conventional cavitation tunnels. When investigating the supercavitating propulsors at small advance coefficients and small cavitation numbers the use of the cavitation tunnel becomes altogether impossible due to "blockage" of the cross section of the working section by the cavities. In order to conduct the experimental investigation in such cases there were built the cavitation basins [22], [23], which have sufficiently large cross section and a free surface, providing almost complete annihilation of the influence of walls, and enables studies of the influence of the free surface.

Note that out of the three existing in the world (cavitation) depressurized towing tanks the first one had been built in the 60s in Russia [22], having dimensional of 50x5x5 meters (length, width and depth correspondingly). In Holland was built a depressurized towing tank with dimensions 240x18x8 meters. More than 8 hours are needed to obtain vacuum constituting 4% of that of the atmospheric pressure [23].

However, the speed of the motion of model in the cavitation basins is restricted by approximately 4m/s, allowing to conduct the tests of the screw propeller model of the diameter 0.2 m in the operational regimes corresponding (based on equal Froude numbers) the speed of the full-size propeller not exceeding approximately 20 kn (assuming that the diameter of the full-size propeller is less than 1.2 m). For the experimental study of the supercavitating propellers at the regime of maximum speed it is far from being sufficient. Therefore the tests for such propellers in the cavitation basin can only be conducted without account of Froude numbers, but, as opposed to the cavitation tunnel, for any magnitudes of advance coefficient, including the regime of “blockage”. At present the cavitation basin is often used to study cavitation on a model of a conventional screw propeller, operating in the nonuniform following wake behind the hull of a ship model although this wake is known not to completely correspond to that of a full-size ship.

An alternative to cavitation basins which appeared in the 60s are cavitation tunnels with free water surface, enabling to account both for the presence of a free surface and the ship hull. For example Free-surface Cavitation tunnel K27 in Berlin Technical University [35]. But it is difficult to receive the smooth condition of the free water surface in this equipment.

For this reason investigators returned to build the cavitation tunnel but differ on conventional tunnel with very big working section. The largest and most capable cavitation tunnel in the world is located in Memphis, Tennessee, USA, reaches 18 m/s, which allows to cover the speed range of the full-size propeller when testing up to the speeds of 70 kn. The cross section of the working section constitutes 3x3 m., which allows to test the propeller models together with that of ships in a scale from 1/10 to 1/20, and to decrease the influence of the walls down to an acceptable level [59].

The full-size experiment (to a very restricted extent) and mostly the propeller testing in the numerous conventional cavitation tunnels (there are approximately 66 tunnels in the world today [59]) constitute the main source of the contemporary experimental knowledge about the supercavitating and strongly cavitating screw propellers.

2.2. Development and Testing of a Series of Supercavitating and Strongly Cavitating Screw Propellers, Examples of Their Use for Full-Size Hydrofoil Ships

In the first part of the lecture let's dwell experimental investigations, connected with the development of a small number of full-size hydrofoil ships equipped with supercavatating propellers.

Cavitation of propulsors, leading to erosion, vibration, hydro-acoustic noise and undesired change of the hydrodynamic characteristics, represent a physical phenomenon, hindering the effort of the ship builders to increase the speed of both the conventional displacement ships and high-speed ships with dynamic principles of support. Sometimes, the whole set of technical problems accompanying occurrence and development of cavitation is called a "cavitation barrier".

In some cases it is possible to avoid the aforelisted consequences of the cavitation occurrence by way of designing a completely noncavitating propulsor. The proper selection of the expanded area ratio of the screw propeller has for a long time permitted to avoid (completely or partially) the development of the cavitation forms resulting in erosion of the screw propeller blades. However, as indicated in the documents of the command of the German Navy dated 1932, they did not manage to avoid strong erosion damage of the propellers of the destroyers and torpedo boats by the latter method [3]. In 200 hours of full-speed cruising the indicated screw propellers would acquire such a damage (erosion blisters of size of a fist), so that their replacement became inevitable. According to the present views [4], one can ensure an acceptable service resource of the screw propellers of ships up to the cruising speeds of 36 knots and even more by means of an optimal selection of the expanded area ratio, frequency of rotation and diameter, in combination with application of the skew contours and improved profiling as well as by taking measures to smooth out the nonuniformity of the following wake. The aforementioned measures can ensure complete absence of cavitation or its very insignificant development, which practically does not result in the erosion damage. For example, a prototype passenger hydrofoil "Taifun" (65t, 2x1750 hp, 100 passengers, [20]) with automatically controlled deeply submerged hydrofoils ship, built in Russia in 1971 reached a speed up to 44 knots with use of two non-cavitating screw propellers mounted on struts (pushing type arrangement)

However, in many cases, it is impossible to design a non-cavitating propulsor. For example, this is the case when the following peculiarities take place simultaneously or separately: high full speed, mounting of the screw propeller on an inclined shaft, nearness of the free surface, too large expanded area ratio (> 1.2), needed to avoid cavitation.

An alternative to the design of the non-cavitating propulsor is naturally an idea of designing a cavitating propulsor which is only to a small extent exposed to erosion and other negative consequences of cavitation. This idea was first set forth in 1941 for the purpose of design of the screw propellers of destroyers and similar ships by a Russian academician Valentin Lvovich Pozdunin [7],[8],[9].[10]. He proposed to select a expanded area ratio, distribution of pitch, section curvature and the form of the sections (Fig. 2) in such a way, that the blades of the high- speed ship screw propeller should operate in the regime of supercavitation. More specifically, in such a regime when the cavities formed on the blades have a length exceeding the local chord, and, therefore close at a certain distance behind the blade (Fig. 3). Therewith, the erosion which usually occurs when the cavities close on the blade surface would not occurs in the supercavitating regime. If additionally, one minimizes the time of the transient ship regime for which the cavities have a length less than the local chords, the unfavorable consequences of the cavitation would not exceed reasonable limits.

Based on intensive experimental investigations in the cavitation tunnel Pozdunin revealed the main difficulties hindering the realization of his idea. First of all, it turned out to be of preference for the supercavitating propellers to employ a special wedge-type profiling (Fig. 4, 5), drastically different from the one traditionally used for the noncavitating screw propellers. Further on, in Russia they started to call supercavitating those propellers that have a wedge-type profiling. And to designate the supercavitating propellers with a segment-type profiling a term highly cavitating propellers was introduced.

The wedge-type profiling and the peculiarities of the flow past the SC propellers immediately gave birth to several problems. First of all, the problem of securing a local strength of thin wedge-type leading edges of the blades which would be sufficient for the full-size propeller. Secondly, the necessity of securing at the regime of full cruising a sufficient length and thickness of the cavity in all sections with a certain reserve for the cavitation occurrence on the pressure side of the blade. Thirdly, the necessity of securing of a sufficient thrust of the propulsor at the intermediate regimes, e.g. at the regime of the drag hump of the hydrofoil ship. The latter problem turned out to be rather important for the design of the hydrofoil ship as a whole and will be considered later in more detail, as there emerged historically two different ways of its solution, namely, the American one and the Russian one.

For the destroyers and torpedo boats the idea of Pozdunin was not realized, as it appeared in the process of experimental investigation that it is only reasonable to employ the SC propellers for by far larger magnitudes of the cruising speed, more specifically, at speeds higher than 50 knots, or for the local cavitation number at 0.7 of the propeller radius less than 0.045. In other words, with the purpose of obtaining sufficiently long cavities, if at all possible, it would be necessary to abruptly increase the angles of attack of the blade sections which would result in an unjustified augmentation of the cavitation drag and a sharp drop of the efficiency. The problem of erosion destruction of the screw propellers of the torpedo boats due to cavitation at the root sections of the blades, was successfully resolved by way of drilling anti-erosions orifices [11].

A complete realization of the Pozdunin's idea was effected in mid-50s by the researchers of the David Tailor Model Basin A.J. Tachmindji and W.B. Morgan [12], E.B.Caster [13] et al. As recollected by M.P.Tulin [1], these specialists started investigation of the SC propellers in the United States (1957) with a design by means of calculations (using quite an approximate lifting line theory) of a model of a two-blade SC propeller with wedge-type profiling. Therewith, the profile of the section was adopted in the form of the so-called 2-parametric optimal profile found with use of the linear two-dimensional theory of M.P.Tulin for zero cavitation number [14] (see Fig.5). Testing of this model completely confirmed sufficient accuracy of the adopted method of the design calculation. Further on this success allowed to develop by means of calculation series of 2, 3 and 4-blade SC propellers [13]. Testing of separate models in the cavitation tunnel also confirmed sufficient accuracy of the calculated results. For example, for the model of a supercavitating 3-blade screw propeller with expanded area ratio 0.5 and pitch ratio 1.57 there were obtained in the course of the experiment for a advance coefficient 1.125 and axial cavitation number 0.3 the thrust coefficient 0.140 and efficiency 0.685, which turned out to be just 2.2% less that the calculated one [12]. In 1962 under guidance of M.P.Tulin the specialists of the company "Hydronautics" successfully developed a 2-blade SC propeller for a gas-turbine hydrofoil ship "Denison" (80 ton, 60 knots, 10000 hp) [1],[15]. Therewith, the form of the pressure side coincided with that of the Tulin's 2-parametric foil, similarly to the aforementioned series, and the thickness was augmented up to the parabolic one. Especially big difficulties arised in securing a sufficient thrust at the regime of the drag hump, but this matter would be considered in more detail later on. Here we would only mention that these difficulties were connected with a phenomena of the flow "blockage" by the cavities typical for the SC propellers at the magnitudes of advance coefficient significantly less than those corresponding to the maximum speed for the given ship project.

In mid-60s there was built a Canadian open ocean hydrofoil ship "HMCS Bras d'Or" (235 ton., 60 kn., 22000 hp) with two SC propellers [16]. When developing these propellers special attention was attached to the investigation of the local strength in the vicinity of the leading edge.

In 1958, i.e. practically at the same time as the U.S. specialists, a Krylov Institute researcher Yu.M.Sadovnikov conducted testing of a series "K" of the SC propellers with wedge-type profiling and symmetric contour [17],[18],[19],[20], comprising 15 two -blade models and 9 three-blade models of the 0.2 m. diameter. The propellers had a relative radius of the hub 0.165, expanded area ratio varied in the range 0.34-1.11, pitch ratio varied in the range 1.0-1.8, and the minimal axial cavitation number reached 0.3. The action curves of one model of this series are presented in Fig. 6. However, the full-size hydrofoil ship with the screw propeller of this series was never built, because for them problem of providing sufficient thurst at the drag hump regime was not solved for this series (see more details further on). The effective solution of the aforementioned problem in the Russian version (when the advance coefficient at the drag hump regime differs only slightly from that in full cruising speed due to drop in rpm) was solved by replacing the wedge-type profiling by the segment-type one (see, Fig.4). Further on, as indicated, adopted in the KSRI (and in Russia) was the term highly cavitating propellers for the SC propellers having the segment-type profiling.

Thus, the distinction between the highly cavitating propellers and the supercavitating propellers consists in the profiling (see Fig.4). In particular, instead of the wedge-type chordwise thickness distribution used is the segment distribution without shifting of the maximal thickness from the midchord ("CK" series) or with shifting of the maximal thickness 15% upstream of the midchord ("CK2" series).

The "CK" series is that of 3-blade highly cavitating screw propellers which was developed and tested in by V.D. Tsapin, and comprises 28 models with expanded area ratio in the range 0.65-1.10 and with pitch ratio in the range 1.0-2.2 [17]],[18],[19],[20]. Fig. 7 gives the characteristic curves for one of the models of this series, and the following Table 1 provides a comparison of the hydrodynamic characteristics of this model with the similar one of the series "K" of the supercavitating screw propellers, the characteristic curves of the latter being shown in Fig.6.

It can be seen from the Table that in the SC regime, when the hydrofoil ship has a maximal speed and the axial cavitation number is equal 0.3, the efficiency of the propeller with wedge-type profiling ("K" series) is 12 - 16% higher than that of the propellers with segment-type profiling ("CK" series). This can be explained by a smaller thickness of the leading edges for the wedge-type series, leading to the decrease of the cavity thickness and the cavitation drag of the propellers of this series. The general strength provided therewith is approximately the same at the expense of larger thickness of the trailing edges for the wedge-type series, although the local strength in the vicinity of these edges is noticeably lower.

Table 1. Comparison of characteristics of two screw propellers with an expanded area ratio 0.81/0.8 and pitch ratio 1.4, belonging to the series “K” of SC propellers with wedge-type profiling and a series “CK” of highly cavitating propellers with segment profiling (see Fig.6 and Fig,.7), (J-advance coefficient, K_T -thrust coefficient, η_0 -open water propeller efficiency)

J	Axial cavitation number	K_T "K"	K_T "CK"	η_0 "K"	η_0 "CK"	$\Delta\eta_0/\eta_0$ in %
0.8	0.3	-	-	-	-	-
0.9	0.3	-	-	-	-	-
1.0	0.3	0.100	0.095	0.600	0.533	12.6
1.1	0.3	0.115	0.103	0.655	0.565	15.9
1.2	0.3	0.098	0.099	0.630	0.560	12.5
0.8	1.0	0.225	0.215	0.562	0.515	9.1
0.9	1.0	0.230	0.248	0.620	0.588	5.4
1.0	1.0	0.200	0.250	0.640	0.660	-3.1
1.1	1.0	0.150	0.208	0.590	0.700	-18.6
1.2	1.0	0.100	0.161	0.520	0.709	-36.3
0.8	Atmosphere	0.315	0.348	0.560	0.562	-0.4
0.9	Atmosphere	0.250	0.300	0.618	0.619	-0.2
1.0	Atmosphere	0.200	0.253	0.625	0.667	-6.7
1.1	Atmosphere	0.150	0.208	0.620	0.700	-12.9
1.2	Atmosphere	0.100	0.161	0.575	0.709	-23.3

On the other hand the series “CK” with the segment profiling has much larger efficiency (more than 18% larger) as compared to the "K" series at the regime of drag hump, when the speed of the hydrofoil constitutes about 50-65% of the maximal speed, which corresponds e.g. to the axial cavitation number equal to 1.0 or slightly larger. Therewith, the advance coefficient only slightly differs from its magnitude 1.15, corresponding to the maximal efficiency of both screw propellers at the maximal speed regime. The case described herein corresponds to a Russian variant of the design of the hydrofoil ship, when the power plant (not having large reserve of power) allows a reduction of the frequency of rotation of the propeller at the drag hump (almost proportionally to the drop of the translational speed of ship) as a consequence of growth of the turning moment and, therefore the advance coefficient at the drag hump regime is only slightly less than its own magnitude at the maximal speed regime.

In the case under consideration the increased efficiency of the propeller at the drag hump regime becomes a decisive factor for choosing the series "CK", as the series "K", due to reduced efficiency and for available power simply does not provide sufficient thrust at the drag hump regime. Note that at the drag hump regime, the hydrofoil ship, as opposed to the displacement ship, has a drag, and hence a required thrust of propulsors close or even exceeding that of the maximum speed.

The U.S. approach to the considered problem of design of the hydrofoil ship radically differs from the Russian one described above. The power plant, for example, gas turbine, is chosen in such a way as to have a sufficient reserve of power to ensure constancy of the frequency of rotation of the propeller for all regimes from that of the maximal speed up to that of the drag hump. Then according to formula (1), the advance coefficient at the regime of drag hump would drop in comparison with that of the maximal speed some 50-35%, i.e. in proportion to the drop of the speed of the translational motion of the ship. Therewith, as follows from the Table 1 given above, (for axial cavitation number of 1.0 or higher) the efficiency of the propellers of the series “K” with wedge-type profiling is more than 9% higher than that of the series “CK” propellers with the segment-type profiling. Consequently, if one use the U.S. approach to the design, the preference should be given to the series "K" with wedge-type profiling which had been done in reality by the American and Canadian specialists when developing the SC propellers for the aforementioned hydrofoil ship "Denison" and an open ocean hydrofoil ship "HMCS Bras d'Or". It should be noted, however, that the U.S. specialists encountered additional difficulties, related to peculiarities of operation of the SC propeller for small advance coefficient- the aforementioned “blockage” effect.

The comparison presented above was made for the two concrete propellers of the indicated two series, having identical number of blades, blade contours, expanded area ratios, pitch ratios, form of the pressure surface and magnitudes of the advance coefficient, but different distribution of the section thickness chordwise. More complete comparison requires analysis of both series, as the advance coefficients, pitch and expanded area ratios for each of the compared propellers are not necessarily equal, and may be taken as optimal for the corresponding series, i.e. may be taken correspondingly to the maximal efficiency for a given cavitation number. The data required for a more complete analysis are given in the Table 2.

Table 2. Comparison of characteristics of two 3-blade optimal screw propellers at axial cavitation number of 0.3, belonging to the series “K” of supercavitating screw propellers with wedge-type profiling and a series “CK” of highly cavitating screw propellers with segment-type profiling (J-advance coefficient, K_T -thrust coefficient, η_0 - open water propeller efficiency, A_E / A_0 -expanded area ratio, P/D-pitch/diameter ratio)

axial cavitation number	series	aim function	A_E / A_0	P/D	J	K_T	η_0	$K_{DT} = J / \sqrt{K_T}$	$1/K_{NT}^2 = \sqrt{K_T} / J^2$
0.3	"K"	max η_0	0.81	1.4	1.12	0.120	0.660	3.233	0.276
1.0	"K"	not opt	0.81	1.4	1.12	0.140	0.610		
1.0	"K"	not opt	0.81	1.4	0.70	0.195	0.490		
0.3	"CK"	max η_0	0.95	1.8	1.50	0.177	0.660	3.565	0.187
1.0	"CK"	not opt	0.95	1.8	1.50	0.209	0.706		
1.0	"CK"	not opt	0.95	1.8	0.90	0.290	0.457		

Comment: the last two columns contain the coefficients, which should be multiplied by the identical for both compared variants multiplier (if identical are the fluid density, thrust and the speed of advancement in free water) with the goal of determining the diameter and the frequency of rotation for the optimal (in efficiency) screw propeller of the corresponding series complying with the considered conditions.

A straitforward analysis of the data given in the Table 2 shows that, as opposed to comparison for the same advance coefficient and other identical parameters, in the case considered here of the maximal speed regime (and axial cavitation number equal to 0.3) no advantage is found in the maximal magnitude of the efficiency of the either series under comparison, because the efficiencies of the optimal wedge-type screw propeller of the “K” series and the optimal segment-type propeller of the “CK” series are identical and equal to 0.66. It should be recognized, however, that this magnitude is reached at different magnitudes of the advance coefficient, expanded area ratio and pitch ratio.

A deeper analysis shows that for given fluid density, thrust of the propeller and the speed of the ship, the optimal propeller of the “K” series would have 10% smaller diameter and 48% larger frequency of rotation as compared with the optimal series “CK” propeller. Increased frequency of rotation and reduced diameter (for identical other conditions) stipulate a substantial advantage of the series “K” propellers with the wedge-type profiling at the maximal speed regime.

The final choice of the series is again defined by the adopted variant of the design of the hydrofoil ship as a whole. If one use the Russian variant, when the advance coefficient at the drag hump regime is only slightly different from that at the maximal speed regime, the preference should be given to the “CK” series with the segment profile, as it follows from the Table 2 that the efficiency of the propellers of this series at the drag hump regime in this case (axial cavitation number 1.0, J=1.5) is 15.7% higher than for the propellers of the “K” series. Notwithstanding the indicated advantages of the “K” series at the maximal speed regime, both in the case considered here and in the course of the analysis of the Table 1, the increased efficiency of the propellers at the drag hump regime becomes a crucial factor for selection of the “CK” series because the “K” series (due to reduced efficiency) for the lack of a sufficient reserve of power (Russian variant) simply cannot provide sufficient thrust at the drag hump regime.

On the other hand, if the U.S. approach is employed to the design of the hydrofoil ship as a whole, when both the frequency of rotation is almost constant, and the advance coefficient at the drag hump regime is much less than its magnitude at the maximal speed regime (in the Table 2 the magnitude of the advance coefficient is decreased on 40%) the preference when selecting the series should be given to the “K” series with wedge-type profiling because the efficiency of the propellers of this series at the drag hump is (axial cavitation number 1.0, J=0.7) is 7.2% higher than for the propellers of the series "CK".

Thus, the comparative analysis of the propeller series differing only in the shape of the section, both for the same advance coefficient (based on the Table 1), and for the propeller at the optimal advance coefficient (based on the Table 2), leads to one and the same conclusion. For almost constant advance coefficient (Russian variant) advantageous is the segment profiling, whereas for almost constant rpm (U.S. variant) the advantage is on the side of the wedge-type profiling.

Another important conclusion can be made on the basis of the foregoing material. When designing a supercavitating or a highly cavitating propeller for a hydrofoil ship the project optimization at the regime of maximal speed should be performed in such a way that a sufficient thrust be provided at the drag hump regime with account of the power plant available on board. In short, the high efficiency at the maximal speed regime is not the only requirement when designing a supercavitating or a highly cavitating propeller for a hydrofoil ship.

Further progress in the development of the supercavitating or a highly cavitating propeller in Russia was connected with a more complete utilization of the computational methods of the vortex theory. In 1970 A.A.Russetskiy and E.A.Fisher in the KSRI employed the lifting line theory with a number of corrections, including those to approximately account for the presence of cavities in the inter-blade space [17]. It is interesting to note that this approach was semi-empirical, as it made use of the experimental data for the determination of the cavities’ thickness at the trailing edge of the blade [24]. Most certainly, the mentioned experimental materials were valid only for the design of such propellers which differed but slightly from the tested ones.

Based on the described approach there was designed a small series of 3-blade highly cavitating propellers "CK2", comprising 4 models with expanded area ratio 0.9 and a radius-wise variable pitch ratio, varying in the range 0.9-1.6 at the radius 0.6. An interesting peculiarity of the form of the profiles of this series consisted in a shifting of the maximal of thickness and curvature of the pressure surface 15% from the midchord to trailing edge of cylindrical sections, while retaining of practically segment form for the corresponding distributions for the region of the leading and trailing edges. Therewith the thickness of the leading part of the profiles decreased, which served to augment the efficiency at the full speed regime, but, simultaneously, should diminish the strength in the region of the leading edges.

Table 3. Comparison of characteristics of the two 3-blade optimal screw propellers with axial cavitation number 0.3, belonging to the series of supercavitating "CK2" and the series of highly cavitating screw propellers "CK3" (J-advance coefficient, K_T -thrust coefficient, η_0 -open water propeller efficiency, A_E / A_0 -expanded area ratio, P/D-pitch/diameter ratio)

axial cavitation number	series	Goal function	A_E / A_0	P/D on r=0.6	J	K_T	η_0	$K_{DT} = J / \sqrt{K_T}$	$1 / K_{NT}^2 = \sqrt{K_T} / J^2$
0.3	"CK2"	max η_0	0.95	1.36	1.08	0.115	0.645	3.185	0.291
1.0	"CK2"	not opt	0.95	1.36	1 .08	0.205	0.690		
1.0	"CK2"	not opt	0.95	1.36	0.70	0.165	0.470		
0.3	"CK3"	Max η_0	0.95	1.56	1.24	0.150	0.680	3.202	0.252
1.0	"CK3"	not opt	0.95	1.56	1.24	0.220	0.708		
1.0	"CK3"	not opt	0.95	1.56	0.60	0.175	0.360		

Comment: The last two columns contain the coefficients, which should be multiplied by the the same multiplier for the variants under comparison (if identical are fluid density, thrust and speed of translational motion in free water) with the goal of determining the diameter and the frequency of rotation for the optimal (in efficiency) screw propeller of a given series complying with conditions considered.

The results of the testing of the models of this series (see, Table 3) showed, that no gain was obtained. In the maximal magnitude of the efficiency in comparison with the "CK" series. However, one was able to reduce relative advance coefficient corresponding to the maximal efficiency (1.08 instead of 1.50 for the series "CK"), which led (inspire of the decrease of the thrust coefficient) to a possibility to reduce diameter of the optimal screw propeller for this series by 12% as compared to the optimal and identical in thrust screw propeller of the "CK" (therewith the frequency of rotation increased by 56%).

Comparing with the data of the Table 2 for a conditional drag hump regime, one can notice, that for the constant advance coefficient (Russian variant) the screw propeller of the "CK2" series has 2.3% less efficiency than the propellers of the "CK" series. At the expense of the shifting of the maximum of efficiency toward smaller advance coefficients the screw propellers of the "CK2" series have noticeably larger efficiency at the maximum speed regime when the axial cavitation number equals 0.3, as compared to the propellers of the "CK", if the comparison is conducted for the advance coefficient less then 1.2 (see Table 4). For example, for J=1.0 the augmentation of the efficiency constitutes 18.2%.

Table 4. Comparison of characteristics of three propellers with expanded area ratio 0.95 and pitch ratio 1.4, 1.36, 1.33, belonging to the series of highly cavitating propeller "CK", "CK2", "CK3" series correspondingly (J-advance coefficient, K_T -thrust coefficient, η_0 -open water propeller efficiency)

J	axial cavitation number	K_T "CK"	K_T "CK2"	K_T "CK3"	η_0 "CK"	η_0 "CK2"	η_0 "CK2"
0.8	0.3	-		0.115	-	-	0.535
0.9	0.3	-	0.1	0.110	-	0.580	0.590
1.0	0.3	0.111	0.115	0.110	0.545	0.630	0.635
1.1	0.3	0.125	0.110	0.110	0.591	0.645	0.650
1.2	0.3	0.124	0.080	0.085	0.616	0.590	0.600
0.8	1.0	0.248	0.200	0.210	0.528	0.545	0.560
0.9	1.0	0.273	0.230	0.235	0.601	0.610	0.620
1.0	1.0	0.257	0.230	0.220	0.657	0.665	0.670
1.1	1.0	0.208	0.193	0.180	0.688	0.695	0.695
1.2	1.0	0.160	0.150	0.135	0.692	0.700	0.690
0.8	Atmosphere	0.356	0.330	0.340	0.555	0.770	0.585
0.9	Atmosphere	0.304	0.285	0.285	0.609	0.620	0.630
1.0	Atmosphere	0.257	0.238	0.230	0.657	0.665	0.670
1.1	Atmosphere	0.208	0.193	0.180	0.688	0.695	0.695
1.2	Atmosphere	0.160	0.150	0.135	0.692	0.700	0.690

In 1980 on the basis of the lifting surface theory for noncavitating propellers with account of the cavity thickness, modeled with a prescribed distribution of the simple layer (the intensity of which was approximately determined with use of the previously mentioned experimental data on measurement of the cavity thickness at the trailing edge [24], [17]) in the KSRI there was developed a small series of highly cavitating propellers “CK3". With the purpose of providing sufficient strength the thickness of the leading part of the profiles of this series was increased in comparison with the "CK2" series. The form of the profile was taken of segment-type and symmetric with respect to the midchord, as in the "CK" series, i.e. the idea of shifting the maximal of thickness and curvature was abolished in this series. Some data on this series are presented in the Table 3 and the Table 4. It is seen that the last of the considered series is the best from all viewpoints. For example, the optimal (in efficiency) at the regime of the maximal speed screw propeller of this series has a record-breaking high efficiency of 0.68, which is 3% higher than for the analogous magnitudes of the series "K" and "CK".

The last of the described series of highly cavitating propellers "CK3" (with the segment profiling) was directly employed at the beginning of the 80s during the design of the full-size highly cavitating propellers for the largest in the world (displacement about 465 t., power of gas turbines 3x18000 hp plus power of diesels 2x1100 hp and the speed of cruising of 63 knots [21]) of the Russian open ocean hydrofoil ship "Sokol". The highly cavitating screw propellers in number of 6 were mounted in pairs on three angular struts. The sense of rotation of each pair was opposite. At full speed the blades of the propellers operated in the regime of supercavitation, although the profiling adopted was the segment one (without shifting off the mid-chord of the maximal of thickness and curvature), and not of wedge-type, as proposed by academician Pozdunin.

The comparative tests of two projects of open ocean hydrofoil ships were conducted in Russia. Besides the hydrofoil ship "Sokol", tested was the hydrofoil ship "Uragan" (426 t., 2x18000 plus 2x1100, 60 kn.), which had two struts and four highly cavitating screw propellers of the "CK" series [21]. A complete set of full-size tests showed that, the hydrofoil ship “Sokol” has evident advantages as compared to the hydrofoil ship “Uragan” (mainly due to a better arrangement of wing system, and, after some improvements (in particular, the power was decreased down 2x20000 hp plus 8000 hp) the former ship can be built in series. Until 1990 there were built 3 serial ship of "Sokol" type, after that the funding of the corresponding programme was stopped [21].

Thus, in Russia in the period of 1941-1980 there were carried out extensive experimental tests (tested were 4 series) of the suparcavitating and highly cavitating propellers.

The analysis of this materials revealed, in particular, an important peculiarity of such propellers, namely, for a given low cavitation number and at a given magnitude of the advance coefficient the increase of pitch for the supercavitating or highly cavitating propeller, as opposed to a noncavitating one, does not lead to a significant increase of the thrust coefficient. This shows that, firstly, use of variable pitch does not bring about the same effect usually anticipated for the noncavitating propeller, and, secondly, for a limited diameter of the SC propeller the thrust generated at the design regime may be insufficient for propelling the ship with a given speed for any choice of pitch.

With the goal of overcoming of the latter problem effective may become the application of the supercavitating propeller with a spoiler at a (rectilinear in radial direction) trailing edge. For the experimental investigation of models of such screw propellers there was developed and tested in the KSRI a model of 3-blades supercavitating propeller with expanded area ratio 0.8 and pitch ratio 1.4, having a wedge-type profiling and an asymmetric rectified contour with the trailing edge rectilinear in radial direction, adapted for mounting of a spoiler with regulated extenuation from -3% to +5% of the local chord. The tests of this mini series of supercavitating propellers with a spoiler showed that for a 2% spoiler (cavitation number 0.4, advance coefficient 1.2) the thrust coefficient increases as compared to the propeller without the spoiler 100% and reaches the value of 0.15. Therewith, the efficiency at the indicated advance coefficient even increases several percent, for smaller advance coefficients a drop of the efficiency of 2% accompanied by the growth of the thrust of 40-50%. The effect of the spoiler estimated in the latter experiment complies, at least quantitatively, with the results of theoretical research on the influence of a spoiler within an ideal fluid mathematical models [25] - [28], [31]. In particular, it was established by calculation that at the regime of its most favorable influence the spoiler provides a significant decrease of the cavity thickness in the inter-blade space, as compared to a similar profile without the spoiler. The latter effect corresponds to shifting of the center of action of the loading distribution chordwise in the direction of the trailing edge. Positive influence of such a shift upon the hydrodynamic lift-to-drag ratio of supercavitating foils at zero cavitation number was found by M.P.Tulin [14] back in 1955.

At the beginning of the 80s there was built and successfully tested a hydrofoil ship "Antaris" (200 t, 60 kn.) with supercavitating screw propellers with spoilers corresponding to the aforementioned mini-series. It is interesting to note that the propellers on this ship were installed on the inclined shafts, and, consequently, at speeds about 50 knots there was observed a breakthrough of the atmospheric air along the inclined shifts to the propeller blades. With the goal to secure a required thrust along with a possible ventilation there were chosen for this particular hydrofoil ship the supercavitating propellers with spoilers.

The story of the application of the supercavitating (or highly cavitating) screw propellers proper, which started successfully in 1962 from the hydrofoil ship "Denison", finishes over by the end of 80s, because the experience of operation of this screw propellers on the world largest serial hydrofoil ships of the "Sokol" type showed insufficient reliability of the shaft sealing on the nacelles and ensuing necessity in frequent repair. The problem of reliability become so acute that it was decided to equip the next projects of the Russian open ocean hydrofoil ships not with supercavitating propellers but with wateriest similarly to the U.S. hydrofoil ships "Tucumcari" and "Pegas".

However, these projects have not been realized. Further on, unfortunately, the interest toward the hydrofoil ships in the world dropped quite abruptly in connection with appearance of more prospective types of high-speed ships, such as catamarans, SES (Surface effect ships) and SWATH (Small water-plane area twin hull), for which the implementation of the supercavitating propellers proper is not preferable.

2.3. PRESENT DEVELOPMENT OF THE IDEAS OF ACADEMICIAN V.L. POZGUNIN

In spite of the evident end of the story of the application of the supercavitating propellers proper, the idea itself, lying in the basis of the development of supercavitating propellers and formulated in 1941 by V.L. Pozdunin as an idea for design of a cavitating (or ventilated) propulsor, less subject to erosion and othernegative consequences of the cavitation (or atmospheric ventilation), found its further evolution in the development of several new types of propulsors. Namely, highly-skewed cavitating propellers, trans-cavitating propellers, surface piercing propellers (or semi-submerged propellers) and ventilated wateriest, which are already in use or have good perspectives for their use on high-speed ships of different types.

Let’s start our consideration with highly-skewed cavitating propellers, intended for the passenger hydrofoil ships of relatively small displacement, which haven inclined shaft and shallowly submerged hydrofoils. As established above, the supercavitating propellers have been used mostly on the sea-going hydrofoil ships, equipped with deeply submerged hydrofoils. However, the “cavitation barrier" is also encountered when designing propulsors for small passenger hydrofoil ships on shallowly submerged hydrofoils. The first of those ("Raketa", 25 t., 38 kn., 1200 hp, 66 passenger) was built in Russia by the design of R.E. Alexeev in 1957. In this case, inspite of moderate speed, it is not possible to avoid cavitation at the maximal speed regime because of the unsteadiness of the flow past the blades of the screw propellers, mounted on the inclined shaft (the angle of inclination of the shaftline varies for different projects in the range of 6-15 degrees). Moreover, in this case breakthrough of atmospheric air is possible through the suction zone along the inclined shaft to the blades of the propeller.

During the first stage of the investigation of this problem in the KSRI there was developed a special series of 5-blade screw propellers, adapted for operation in oblique flow field. These propellers were designed by E.P.Georgievskaya under guidance of Professor A.A.Rousetsky mostly for the purpose of securing the absence of cavitation, and, consequently, the absence of erosion on the pressure side of the blades [11]. Therewith, cavitation and erosion on the suction side could not be suppressed, although measures were taken to minimize it (the 5-blade propeller series consisted of 22 models with expanded area ratio 0.8; 1.1; 1.25; 1.4 and pitch ratio in the range of 1.1 - 1.55). However, use of 5-blade propellers of the indicated series did not provide in the considered case the realization of Posdunin’s idea of designing a cavitating propulsor adapted to oblique flow and only slightly exposed to erosion and the other negative consequences of cavitation.

A direct use of the three-bladed supercavitating or highly cavitating propellers with symmetric contour, of the aforementioned series, did not give effect in the case of oblique flow, because unsteady form of cavitation in this case results in a qualitatively different mechanism of the appearance of erosional damage than in axial flow.

In the considered case of oblique flow the mechanism of the appearance of erosional damage, as it was found with use of high-speed photography [5], is connected with a periodical appearance and disappearance of a principally new type of unsteady cavities, which were proposed to be called "residual". In particular, it was found that the busted partial cavity the after further turning of the blade, when the zone of decreased pressure (corresponding to its occurrence conditions) is replaced by a zone of increased pressure, starts to close by way of moving its forward part to its tail part.

The latter does not have time to noticeably move downstream, because of the reestablishment of pressure behind the cavity and high speed of the process. Thus, the main distinctive feature of unsteady residual cavities consists in their collapsing only in their front part, disappearing in the region of its tail. In the region of its disappearance the residual cavity gives rise to an intensive erosion, and the corresponding erosional damage is most visible on the suction side of the 5-blade propeller of the indicated series tailored for operation in oblique flow. Deep understanding of the physics of the process accompanying the operation of the propeller in oblique flow enabled the specialists of the KSRI in 1983 to successfully realize in this complicated (due to oblique flow) case the idea of Posdunin of designing a propeller just slightly subject to erosion and other negative consequences of cavitation. This success was confirmed in September of 1983 in the process of full-size tests of a Russian passenger hydrofoil ship on shallowly submerged hydrofoils "Kometa" (1961, 118 passenger, 60 t., 2x1100 hp) with full cruising speed of 35 kn., on which there were installed the specially developed highly-skewed cavitating propellers (HSCP) [5]. In the process of these investigations was designed a 3-blade HSCP operating on the inclined shaft (with angle 13 degree), having a expanded area ratio of 1.2, pitch ratio of 1.3 and diameter 0.67 m.

The working idea in this case consisted in the concept that for a properly chosen degree of skewing and form of the sections the cavity does not exist permanently as opposed to usual supercavitating propellers, but appears in the form of a dynamic film partial cavity at different moments of time and at different sections of the blade from its suction side, which is determined only by angular position of the considered blade at a given moment time (see Fig.8). The blade is designed in such a way that in the course of its turning (due to the skew and flow downwash), the residual cavity for each blade is dynamically shifting to peripheral sections end, eventually, closes outside of the surface of the cavity (see Fig.8). Therewith the formed front elements of the residual cavity are moving in the direction of the tail part. The latter forms at the end of the whole cycle right before the complete disappearance of the residual, and which finds itself outside the blade surface due to a special form of the blade. With such a closure mechanism of the unsteady residual cavities there is no erosion observed on the whole surface of the blade, although on the larger part of the sections there takes place a dynamically developing partial film-like residual cavity, which periodically (at every rotation) appears and disappears in its turn on every blade (see Fig. 8).

The full-size tests of the hydrofoil ship on a shallowly submerged hydrofoils "Kometa" with the two propellers thus designed showed, that the erosion in practically not observed on them, i.e. the service time of these propellers significantly exceeds that of the initially installed 5-blade custom screw propellers, corresponding to the series described above. Therewith, by means of optimization of the blade geometry the newly developed highly skewed cavitating screw propellers turned out to be 10 % more efficient, that the custom 5-blade propellers [5].

Close to the aforementioned type is a cavitating propulsor called a trans-cavitating propeller. An interesting investigation of a possibility of designing such propellers for the shallow-water ferries, having maximal speed in the range 30-35 kn., was performed by the Japanese researchers [36], [37]. They proposed to design a screw propeller having conventional sections (NACA or MAU) near the blade root and gradually much more pronounced wedge-type supercavitating sections when approaching the tip of the blade. Such mixed-type screw propellers were called "trans-cavitating propellers". In the trans-cavitating regime the suction side of the blade is covered by the cavity only at peripheral radial and is unsteady depending on the angular position of the blade, as the propeller operates in a tangentially nonuniform following wake. It should be noted that in the considered case due to restricted diameter the 4-blade skewed (skew at tip 36 degree) screw propellers were designed for a moderate loading (0.728), more exactly J=0.916(0.720), K_T =0.240(0.148), with the axial cavitation number equal to 1.048 or 1.371, which corresponds to the freely speed equal to 35 or 30 kn respectively. Tested altogether were 11 models of the propellers. The design was carried out with use of the method, enabling to control sheet cavitation on the propeller blades. On the basis of extensive experiments it was found that for a regime, corresponding to the ship speed of 30 kn, a noncavitating propeller with conventional profiling is better, and at the regime, corresponding to the ship speed of 35 kn is worse (in efficiency and the pressure fluctuations), than the proposed trans-cavitating propeller.

Pass over to consideration of the other two out of the listed propulsor types (surface piercing propellers and ventilated waterjets), which, in a general sense, can be viewed as a present stage of the development of the ideas of Pozdunin. The propeller operation on a high-speed ship is performed near a free surface (unless the special measures are taken, e.g. placing the propeller in zone of increased pressure under a hydrofoil), and, obviously, a possible breakthrough of the atmospheric air to the suction side of the blade can considerably diminish the thrust of the propulsor. This breakthrough is called atmospheric ventilation and is completely analogous to supercavitation, but for very low (practically vanishing) magnitudes of local cavitation number. Such low cavitation numbers correspond to the regime of atmospheric ventilation, because in this case the pressure in the cavity equals to atmospheric one, and not the pressure of saturated water vapor at the temperature during the tests, which, e.g for 4 degrees Centigrade constitutes just 0.8% of the atmospheric pressure.

Following the line of thinking of V.L. Pozdunin, in the cases, when the possibilities of avoiding ventilation of the blades of the propeller are exhausted, one may formulate a task of designing a ventilated propulsor, free of negative consequencies of ventilation (cavitation), i.e. free of a uncontrolled drop of the thrust and capable of working in the regime of atmospheric ventilation (in fact, this takes place at the regime of the extremely developed supercavitation, corresponding to almost zero magnitudes of local cavitation numbers). At present known are and have found applications two approaches of the technical realization of the formulated task. Consider these tasks in the same order, in which they started to be used on real high-speed ships.

One of the first applications of the surface piercing propellers (SPP) for the hydrofoil ships was realized in Russia in 1963 [29] with the goal of decreasing some 28% of the draft in floatation (as compared to the hydrofoil ship "Raketa") of the Russian river passenger hydrofoil ship "Raketa-M" (23t., 32.4 kn, 1200 hp, 50 passenger). The draft was decreased from 1.8m to 1.3m by varying the arrangement of the propeller relative to the stern hydrofoil. Therewith, diminished was the angle of inclination of the shaft from 12 to 5 degrees, the pitch of the screw propeller was increased from 0.815m to 0.91m, the expanded area ratio – from 1.0 to 1.45, and the number of blades and diameter remained the same 6 and 0.665 correspondingly [29]. The form of the blade contour was skew-like, the form of the profile was segment one. At maximum speed the propeller was partially immersed (80%), and its blades worked in the regime of atmospheric ventilation (atmospheric cavitation). The developed SPP provided a sufficient thrust on all regimes of the ship motion and turned out to be an acceptable technical solution applied later on on the passenger river hydrofoil ship "Belarus" (14.5t, 32.4 kn, 1200 hp,40 passengers).

These described applications of the first SPP were preceded by a development and testing of a model series of such propellers on a catamaran in open water, covering the range from от 3 to 6 blades, expanded area ratio from 0.685 to 1.285 and pitch ratio from 0.975 to 1.4. The modeling was performed in Froude number and advance coefficient. Almost zero magnitude of local cavitation numbers was provided at the expense of the regime of atmospheric ventilation and no vacuum was needed in this case above the free surface, as opposed to the case of supercavitating propeller, for which, as indicated, the modeling in cavitation number is required. All research was conducted under guidance of a Professor of Leningrad Institute of Water Transport A.M.Basin and an engineer of the Central Hydrofoil Bureau in Gorkiy A.I.Maskalik [30]. The maximum efficiency of this propeller series at a relative submergence of 0.5 turned out to be 0.48, and for the relative submergence of 0.8 turned out to be equal 0.50.

As another example of use of the SPP in Russia one can indicate a cutter "Mustang" (20t, 2x1600, 50kn.) built in mid-80s with a ventilated air cavity on the bottom. In this case the specialist of the KSRI under guidance of F.F.Bolotin managed to obtain higher SPP efficiency equal approximately to 0.6 at the maximal speed regime by means of implementation of the wedge-type profiling (instead of segment one used for the SPP of the hydrofoil ship "Raketa-M").

Operation of SPP on a high-speed ship is characterized by formation of considerable in size unsteady ventilated cavities and a substantial spray phenomenon, related to the process of crossing by each blade (two times per revolution) of free surface (see Fig.9).

In Switzerland Philip Rolla (of Rolla SP Propellers SA) developed and manufactured many SPPs for different high-speed ships. In 1991 were published the results of testing of the series of SPP (4-blades, expanded area ratio 0.8, pitch ratio varied from 0.9 to 1.6) developed by Philip Rolla. The tests were carried out by Professor Klaus F.L.Kruppa in the high-speed free-surface cavitation tunnel of Berlin Technical University [35].

A characteristic peculiarity of SPP is a growth of the efficiency with increase of the ship speed, illustrated in Fig.10 on an example of the cutter "Gentry-Transatlantic" (145 t., 10866 hp, 68 kn, length 33.5m.), which showed in July 1989 a record-breaking time (3733 min) of navigating across the Atlantics with one refueling. Two waterjets (2x3433h.p.) were used on this cutter, driven by the two diesels and one SPP (4000 hp), driven by gas turbine [32].

In Fig.10, borrowed from the aforementioned article, presented was a comparison of the efficiency of the waterjets of this cutter with the efficiency of SPP. One can see that the maximal efficiency of waterjets 0.68 is reached at a speed of 55 kn., and the efficiency of the SPP, also 0.68, has the maximum magnitude at a speed of 70 kn., when the efficiency of there waterjets falls down to 0.55, that is 19% in comparison with the maximum. Therewith it is seen from the presented Figure that the efficiency of the SPP continues to grow up to the maximal speed (see Figure10), and obviously would continue to slowly rise for further growth of speed.

The growth of the efficiency with the speed represents a unique feature of the SPP and is explained by the influence of Froude number, as the local cavitation numbers, as indicated, are close to zero for the SPP blades, and, therefore, the caviotation number does not have any effect in this case. Note in passing that in the case of the supercavitating screw propeller of wedge-type profiling there takes place an opposite situation, i.e. Froude number does not practically influence, and the cavitation number becomes a decisive parameter. For example, according to the data on "K" series (see Table 1) the maximum efficiency of the supercavitating propeller with pitch ratio 1.4 for advance coefficient 1.1 is reached at the cavitation number about 0.4 is equal to 0.675. The indicated maximum for a concrete ship project corresponds to a certain speed so that for the supercavitating propeller there exists a usual maximum of the efficiency versus speed, which is completely analogous to that for the waterjet presented in Fig. 10.

The maximum speed shown by "Gentry-Transatlantic" in the process of its record cruise in good weather and empty fuel tanks, was equal to 74.8kn., and the average speed for the whole distance constituted 55kn. The considered cutter had one 5-blade SPP with the wedge-type profiling, a diameter of 0.914m., pitch ratio 1.36, expanded area ratio 1.05 and the nominal frequency of rotation 1900 revolutions per min. At the intermediate speed of 40kn. The efficiency of SPP (see Fig. 10) drops down to 0.46, i.e. 32% as compared to the maximum magnitude, which similarly to the supercavitating propellers with wedge-like profiling, is the main deficiency of the propulsors of this type.

Some possibilities of improvement of characteristics of the SPP in the intermediate speeds can be obtained by using the controlled pitch SPP (CPSPP). Two such 6-blade CPSPP of diameter 1.07m were installed in 1971 on the experimental skeg-type air cushion vehicle "SES-100B" (105t., 15020 hp, 90.3kn) and, during the full size tests ensured sufficient thrust (even larger the design thrust) at all regimes, starting from that at zero speed. It is interesting to mention that simultaneously in the U.S.A. there was built and tested an analogous experimental skeg-type air cushion vehicle "SES-100A" (114t., 12316 hp, 76 kn), equipped with two waterjets. The tests of both air cushion vehicles showed that for the speeds higher than 70 kn the CPSPP are considerably more efficient than the waterjets, as the speed of the waterjet variant turned out to be 10% less that of the propeller one even accounting for the 22% of excess of the power of the latter.

When developing the CPSPP for the air cushion vehicle "SES-100B" considerable attention had to be attached to the strength and vibration of thin wedge-like blades, accounting for the shock character of the loading at water entry with high frequency of rotation (at 80kn. about 1900 revolutions per min). Unsteadiness of the loading and its shock nature for the blade water entry and exit out of water is an incorrigible deficiency of the SPP, giving birth to serious problems in securing strength and reliability of the whole propulsor installation, especially difficult for solution in the case of increase of of the dimensions of ships.

For small sporting ships the SPP is a sufficiently reliable and wide-spread propulsor, e.g., sporting cutters of the type "FORMULA-1" always have the SPP as a propulsor, with diameter about 0.15m, frequency of rotation about 9000 rpm. This cutters-catamarans with aerodynamic unloading and power of the suspended engine of about 400hp. and the cutter weight (without fuel) of 0.4t reach a speed up to 120kn, and for them important is the unique property of the SPP to increase its efficiency with speed, more precisely with increase of Froude number. When passing to larger ships, as indicated previously, there comes to the foreground the problem of unsteady shock loading, occurring when the blades intersect the free surface.

The original means of the solution of this problem for ventilated propulsor by eliminating the causes of the appearance of unsteady loads is a new type of propulsor proposed in 1975 by a researcher of the KSRI M.A.Mavluydov. This propulsor was called a ventilated waterjet [18], [33]. In fact this is a waterjet with the above-water or partially above-water ejection of the jet, which has an axial pump at the end of the suction part of the waterjet tube which has contact with atmosphere. This pump operates in the regime of atmospheric ventilation, i.e. for the local cavitation numbers close to zero. The blades of the pump should have a wedge-type profiling, sometimes with a cavitator on the suction surface (Fig. 11).

In terms of the peculiarities of hydrodynamic characteristics and the magnitude of the efficiency the ventilated watrejet is similar to the SPP. For example, it possesses to a full degree the aforementioned unique feature of the SPP to increase its efficiency with growth of the speed. However, as opposed to the SPP, during the operation of the ventilated waterjet absent are: the shock loads on the blades, large loads on the bearings and considerable unsteady lateral forces, acting upon the whole ship.

At the beginning of 80s in Russia were built an SES (140t, 2x3000 hp, 35 kn), equipped with two ventilated waterjets located behind the skegs, and a cutter with air cavity on the bottom "Serena" (100t, 2x3000 hp, 30 kn.), equipped by two ventilated waterjets with diameter of working wheel about 1.15m. The latter project is built in series is showed itself quite well in practical operation. The propulsive coefficient of the ventilated waterjets in this case at the full speed regime is equal approximately 0.7 [18].

A certain interest toward ventilated waterjets as a prospective type of propulsors was shown in 2000 by the specialists of the Naval Surface Warfare Center USA, Carderock Division [34].

3. Mathematical Modeling

3.1. Preliminary comments

A necessity for theoretical investigations of hydrodynamics of the supercavitatin propellers was understood right after the formulation of the Pozdunin's idea, as engineers lacked the experience of the development of such propulsors. An intensive work was started begun in this direction in a number of countries. In Russia the pioneering research was carried out by V.F.Bavin, A.M.Basin, M.I.Gurevich, A.N.Ivanov, V.M.Ivchenko, V.M.Lavrientiev, A.D.Pernik, N.N.Polyakhov, O.V.Rozhdestvensky, A.A.Rousetsky, L.A.Epstein, D.A.Efros.

At first its seemed that supercavitating screw propellers would be more efficient than the noncavitating due to reduction of friction on the part of the blade covered by the cavity. However, more detailed theoretical investigations showed that for the supercavitating profiles having a wedge-type leading edge with cavity starting from the leading edge, the suction force is not realized, and therefore, together with the elimination of friction on the side of the blade covered with cavity there appears a specific pressure drag which was called "cavity drag". It turned out in practice that this drag component is comparable in magnitude with the "lost" friction drag. As a result the supecavitating screw propeller has an efficiency which is lower than that the same propeller at a larger advance coefficient and the same cavitation number, when rather than supercavities there occur on the blades partial cavities or no cavities at all depending on the magnitude of the considered cavitation number.

The principal problem of the theory in connection with the discovered new component of losses became that of the optimal distribution of loading along the blade (along radius and along the chord) with necessary account of the requirements on the sizes of the cavities forming on the blades. This problem was previously solved for noncavitating propellers. Therewith, important is both the length of the cavities, which should be larger than the maximum width of the blade (this is the main requirement of the flow regime, which is called supercavitation), and thickness, which should exceed the blade thickness complying with strength requirements. Let's call the formulated problem the problem of the design calculation of the supercavitating propeller (SCP) or the first problem.

The second albeit not less important problem is the so called analysis calculation, which enables obtaining by way of calculations all necessary characteristics of the designed propeller for any regime of its operation. This is a direct problem of hydrodynamic calculation of the SCP, when studied is a flow past a propeller of a given configuration, given advance coefficient and given cavitation number. Therewith, Froude number is not accounted for and the fluid is assumed weightless, as, according to the aforementioned, the account of gravity leads to an unsteady flow problem, for which the local cavitation number, corresponding to a concrete point of the considered cylindrical section of the blade, is a variable, more exactly, a function of the time-dependent angular position of the blade for a horizontal position of the axis of the screw propeller. The importance of the analysis calculation is clear from that the SCP design obtained after the design calculation of the SCP should necessarily secure a sufficient thrust at the intermediate regimes, such as that of the drag hump for a hydrofoil ship. One can surely use the experiment in the cavitation tunnel to determine characteristics of the SCP, but for that one should manufacture the propeller which is impossible to do in the rhythm of the calculations and for many studied variants. Therefore, the actuality of the calculation methods is obvious. At the same time one should note that the complexity of the analysis calculation for SCP consists in necessity to calculate different regimes of flow past the blades bot without cavitation and with development of its different form.

To solve the two above formulated problems one can use mathematical models of different levels. Consider briefly some of the mathematical models developed as of now, not pretending to be complete and referring to the available publications.

3.2. REGRESSION MODELS OF HYDRODYNAMIC CHARACTERISTICS OF THE EXPERIMENTALLY INVESTIGATED SERIES OF THE SUPERCAVITATING PROPELLERS

The simplest albeit very actively employed mathematical models contain regression analysis, describing results of tests of systematic series of the SCP models. Presented in [38], [39] are the coefficients of the regression polynomials, obtained through the analysis of the following series of highly cavitating propellers:

-3-blade "СК" series of highly cavitating propellers [18], [19](Tsapin V.D., Sadovnikov Yu.M., 1955);

-5-blade series of the cavitating propellers adapted for oblique flow operation without erosion of the pressure side, [19](Georgievskaya E.G., Russetskiy A.A., 1965);

-3-blade series of screw propellers Newton R.N., Rader H.P. [40](1961);

-3-blade series of screw propellers Gawn R., Burrill L.C. [41](1957).

The regression polynomial, obtained separately for the thrust coefficient and the moment coefficient, represents these quantities versus advance coefficient, cavitation number, expanded area ratio and pitch ratio. Having such a mathematical model for a given series it is easy to construct the corresponding algorithms for the computer calculation within the design and analysis schemes. The main deficiency of such an approach consists in an impossibility of designing a propeller, going out (in any parameters) of the limit parameters of the series tested in the cavitation tunnel. For example, an impossibility to account for a nonuniformity of the flow coming upon the propeller if the tests of the aforementioned series were conducted in the uniform flow. Besides, there arises a question of design of the series proper and possibilities of their elaboration.

Within the regression mathematical models these questions cannot be solved. To solve them one should make use of different mathematical models of vortex theory of screw propellers. Let’s consider in the following section one of the latter models, developed in 1985 in Leningrad Shipbuilding Institute (now Saint-Petersburg State Marine Technical University) by A.S.Achkinadze and A.S.Narvsky [47], [48], [49], [50], and solving the problem of design calculation of the supercavitating propeller on the basis of the lifting surface theory, and a liner theory of cavitating flows with use of the open model of the cavity closure.

3.3. LIFTING SURFACE THEORY AS A MATHEMATICAL MODEL FOR DESIGN CALCULATION OF SUPERCAVITATING PROPELLERS

Let assume that there are z (according to number of blades) symmetrically arranged proper helical surfaces with a common x-axis, oriented in direction of motion of the screw propeller. Designate one of these surfaces S and consider further on only this nominal surface, automatically accounting for the symmetry of the flow with respect to blades and a necessity of summing up all induced velocity contributions from all indicated z- surfaces.

The geometry of the nominal surface for a given x-axis is uniquely determined by pitch P_S, which is determined by a special algorithm, accounting for prescribed thrust coefficient, advance coefficient K_T, and the parameters of a given nonuniform velocity field. The indicated algorithm is called a Generalized Linear Model (GLM)[42] and is used successfully for the design of not only supercavitating but also noncavitating screw propellers [43], [54].

Take further on, following the linear theory of lifting surface, that the hydrodynamic singularities are continuously distributed upon the nominal surface within the blade and the wake behind it. Therewith, according to hypothesis of the potentiality, it is assumed that the considered fluid is potential in the whole flow domain except the surfaces occupied by hydrodynamic singularities (for all blades). The flow is assumed incompressible, inviscid, gravity-free, unbounded and steady (in a moving coordinate system, attached to a uniformly rotating and uniformly moving along x-axis screw propeller). Then, based on the theory of potential, knowing the potential induced by distributions of a simple layer with scalar intensity q, and a potentialof vortex surface layer of a vector intensity $\vec{\gamma}$, one can integrate over all corresponding domains and find direct value of the perturbation velocity vector:

due to a simple layer

$$\vec{W}_q(X_1,Y_1,Z_1) = grad\left(\frac{-1}{4\pi}\int_{S_q} q\left(\frac{1}{R}\right)dS\right) = \\ \frac{-1}{4\pi}\int_{S_q} q\cdot grad\left(\frac{1}{R}\right)dS = \frac{1}{4\pi}\int_{S_q} q\frac{\vec{R}}{R^3}\,dS \tag{4}$$

due to a vortex layer (both attached and free)

$$\vec{W}_\gamma(X_1,Y_1,Z_1) = \frac{1}{4\pi}\int_{S_G}\frac{\vec{\gamma}\times\vec{R}}{R^3}\,dS \tag{5}$$

where $\vec{R}$ - radius vector, directed from the integrated element toward a point whre the velocity is calculated; S_q- is a part of the nominal surface upon which the simple layer is located; S_G- is a part of nominal surface on which the vortex layer is located.

As known from the theory of potential, in the points of the nominal surface, where the intensity of simple layer is not equal to zero, there is a jump of the normal component of the perturbation velocity and in the points of the nominal surface, where the intensity of vortex layer is not equal to zero, there is a jump of the tangential component of the perturbation velocity. With account of the latter consideration, one has:

For the normal component of the perturbation velocity on the pressure side of the nominal surface (normal vector is positive when directed from the pressure side to the suction side of the nominal surface)

$$W_n^- = W_{qn} + W_{\gamma n} + q/2 \tag{6}$$

for the tangential component, directed along the proper helical lines constituting the normal surface and designated by index τ, component of the perturbation velocity on the suction side of the nominal surface (positive when directed toward leading edge)

$$W_{\gamma\tau}^{+} = W_{\gamma\tau} - \gamma_r / 2 \tag{7}$$

To secure potential character of the flow outside of the considered system of singularities between the radial and tangential components of the vector $\vec{\gamma}$, which does not have a component normal to the nominal surface, there should be fulfilled a known relationship (which is equivalent to the condition of preservability of the vortices or equivalence to zero of surface divergence of vector $\vec{\gamma}$)

$$\gamma_\tau = \partial\Gamma / \partial r \tag{8}$$

where the intensity of the double layer, equivalent to the considered system of distributed continuos vortices equals

$$\Gamma(r,\xi) = -\int_{\xi_{LE}}^{\xi} \gamma_r(r,\xi) d\xi \tag{9}$$

The formulae presented are valid only for the case of absence of discretized vortex lines and zero magnitude of Γ on the contour of the blade and the vortex wake. In this case valid is the relationship, enabling to determine the equivalent vortex distribution for a given distribution of the double layer, namely

$$\vec{\gamma} = \vec{n} \times grad\Gamma \tag{10}$$

Besides the perturbation velocities there must be taken into attention a field of the transport velocity together with the moving coordinate system, which is rigidly connected with the rotating and transitionally moving screw propeller $\vec{V}_E$ and the incoming flow field $\vec{V}_\psi$, so that the field of relative velocity $\vec{V}_R$ in the moving and rigidly attached to the propeller coordinate system can be found with use of obvious formula

$$\vec{V}_R = \vec{W}_q + \vec{W}_\gamma + \vec{V}_\psi - \vec{V}_E \tag{11}$$

Using the corresponding Euler equations integral, the pressure in the fluid in the moving propeller-attached coordinate system can be determined, if found is the total field of perturbation velocity

$$\vec{W} = \vec{W}_q + \vec{W}_\gamma \tag{12}$$

using the formula

$$p - p_0 = -\rho \frac{(\vec{W} + \vec{V}_\Psi)^2}{2} + \rho \cdot \vec{V}_E (\vec{W} + \vec{V}_\Psi) \tag{13}$$

According to the linear approach, the induced velocity and the absolute velocity of the given oncoming flow are assumed being small magnitudes of the first order and the square of their geometric sum can be neglected, then one can derive

$$\begin{aligned} & p - p_0 = \rho \cdot \vec{V}_E (\vec{W} + \vec{V}_\Psi) = \\ & \rho V_{E\tau} W_\tau + \rho V_{E\tau} V_{\psi\tau} = \rho V_E W_\tau + \rho V_E V_{\psi\tau} \end{aligned} \tag{14}$$

where the index τ denotes the projections of the corresponding vectors upon the direction tangential to the proper helical lines constituting the nominal surface. It is more accurate to take the projections of the induced and additional velocity on the direction of the vector $\vec{V}_E$, but the adopted tangential direction differs from the indicated one by a small angle (according the linear approach) so that the relevant error is of higher order of smallness than the retained terms.

Using the formula (3) for the local cavitation number σ and previous equality, one can obtain a linearized dynamic condition on the boundary of the cavity, which physically signifies a pressure identity for points of the cavity boundary with the pressure of the saturated fluid vapor ($p = p_V$),

$$W_\tau^+ / V_E = -\sigma / 2 - V_{\psi\tau} / V_E \quad \text{in } S_{CAV} \tag{15}$$

where S_{CAV} - is part of the suction side of the nominal surface, covered by the cavity in design regime. Note that the domain occupied by the cavity S_{CAV} does not coincide with the projection of the blade contour upon the nominal surface S_B (see Fig. 12).

When deriving (15) account was taken of the fluid being gravity-free, and, therefore, the pressure at the infinity, entering in the local cavitation number, coincides with the Euler integral constant ($p_{0r\theta} = p_0$). The pressure surface S_p of the supercavitating propeller is assumed free of cavitation at the design regime, and, therefore, on this surface (its form is to be determined in the solution process as that of the cavity) there should be fulfilled a kinematic condition of no-normal velocity, which without simplification in the most general way can be written as

$$\vec{V}_R \cdot \vec{n} = 0 \quad \text{in } S_p \tag{16}$$

Now all is ready for the formulation of the considered problem of the design calculation in its least general (basic) form (Formulation of Problem A), when there is no freedom of choice, and, consequently, no possibility to optimize the design.

The problem A consists in finding a geometry of the blades and cavities for a given distribution of loading along the blades of the supercavitating propeller. Therewith, given are the pitch of the nominal surface, the projection of the blade contour upon this surface, diameter of the hub (which is assumed to be infinite and cylindrical), advance coefficient and axial cavitation number χ (which, according to (2) and (3) with account of the absence of gravity forces, is related to σ by an obvious formula $\sigma = \chi \sin^2 \beta$, где $tg\beta = J/(\pi\bar{r})$

If the loading is prescribed, then prescribed is the intensity of the attached vortex layer (i.e. given is the radial component of the vector $\vec{\gamma}$) on the nominal surface within the blade or, which is the same, prescribed is the distribution of circulation along the radia and the blade chord. Unknown in this case is the intensity of the simple layer q, modeling the cavity. Thickness of the blade material in this case is not accounted for at all, as it is assumed that the cavity completely covers the suction side, starting from the leading edge. However, due to the absence of freedom in the choice of the distribution of loading along the blade the obtained solution of the problem A can give an unreal thickness from viewpoint of the strength of the blade, as no additional conditions are envisaged within the basic formulation.

After finding the platform of the cavity (i.e. after finding region S_{CAV}) and determination of the intensity of the simple layer q, distributed along this surface, one can easily find the form of the pressure side of the blade (i.e. find pitch distribution and the form of the pressure side of the section radius-wise) as well as all necessary hydrodynamic characteristics of the screw propeller under design.

Thus, the determination of the form of the cavity platform represent a central point of the problem A. To investigate this problem use a linear theory of cavitating flows and choose as a closure model the open model, proposed in linear two-dimensional case by Fabula [44] (a few months later a nonlinear formulation of an analogous model for the supervcavitation regime was published by Wu, and, for the regime of partial cavitation still a bit later by Bassanini). The choice of this model is not accidental.

As a matter of fact, the closed cavity model in the two-dimensional case predicts an unrealistic growth of lift coefficient of the supercavitating foil when the cavity closure region nears the trailing edge of the foil. This phenomena is called by some authors a “Geurst paradox” [45]. Comparison of the magnitudes of the lift coefficient for a 2-dimensional flat plate, obtained with help of the open and closed cavity closure models are presented in Fig.13. The advantage of the open model for the design regimes when the cavity length equals or nears unity ($\sigma / \alpha = 8$-10 for 2-d flat plate) is obvious. It is left to account that the indicated regime is the most characteristic flow regime for the blades of supercavitating propellers, because the maximal efficiency of these propulsors is reached exactly for a minimal cavity length at every section, i.e. for the minimal length of the cavity by the condition of the absence of erosion. This latter length, as indicated, should only slightly exceed the length of the corresponding chord. Application of the closed model in this case is either incorrect or requires special effort for overcoming the Geurst paradox.

The equation (15) is a 2-dimensional singular integral equation (SIE) with respect to the intensity of the simple layer q with an unknown domain of integration S_q (domain S_q for the sought solution should coincide with the domain covered by the cavity S_{CAV}). This equation is an equation of the considered problem A.

For uniqueness of the solution of the SIE it is necessary to specify the class of functions, in which one seeks the unknown function q and the loading is prescribed, i.e.given is the radial component of the vector of the vortex layer (i.e. the intensity of the attached vortex layer, which is prescribed within the blade). In accordance with the open model the function q should vanish at the rear boundary of the cavity and outside of the domain S_{CAV}. At the front boundary coinciding with the leading edge of the blade, the sought for function q should (the case of rounded leading edge is not considered here) have a quarter-root singularity as for a thin supercavitating plate in the two-dimensional case. Therewith, in all other points the unknown function q is assumed to be sufficiently smooth as a matter of existence of two-dimensional singular integrals.

A traditional approach (see e.g. the work of Kinnas [46]) to treatment of the formulated problem consists in organizing an iterative process with the goal of an approximate determination of the cavity platform. Authors of publications oftentimes attach little attention to matter of convergence, correctness (in the sense of dependence of the result on the initial approximation) and the efficiency of the indicated iterative process. In addition, use of traditional approach excludes a possibility to conduct (by setting free several parameters) a numerical optimization of the project with account of prescribed inequality conditions (it is clear that the conditions, securing sufficient thickness and length of the cavity, can be formulated in advance in form of inequalities).

In the period from 1974 through 1985 Achkinadze developed and (with Narvsky) applied for calculation of supercavitating propellers (for solution of the problem A and other problems) an untraditional method (the method of artificial varifational problem), which enabled using effective methods and programs of linear programming for numerical solution of the stated design problems [51], [47],[48]. Essentially, this untraditional approach allows (as opposed to the traditional one) to account for restrictions in form of the inequalities and (very effectively) organize iterations to determine the cavity's platform with use of the simplex method of linear programming.

Consider untraditional formulation of the problem A in that interesting for us case of the supercavitating regime whereby the cavities, starting at the sharp leading edge, have a length exceeding that of a corresponding local chord everywhere radius-wise, namely:

$$L_{CAV} / c > 1 \quad \text{for} \quad \bar{r} \in [\,\bar{r}_H ; 1 \tag{17}$$

As it is difficult to say if this assumption is fulfilled, one would have a possibility to filter out the calculated results for the cases when it is not valid in the process of calculation.

Variational (nontraditional) formulation of the problem A differs from the traditional one, formulated above, by that:

Firstly, the integral equation (15) would now be satisfied only for the points of a given domain S_B, i.e. for the points corresponding to the suction side of the blade, namely

$$-W_\tau^+ / V_E = \sigma / 2 + V_{\psi\tau} / V_E \quad \text{in } S_B \tag{18}$$

Secondly, for the domain outside of the blade the integral equation is replaced by a corresponding integral inequality

$$-W_\tau^+ / V_E \leq \sigma / 2 + V_{\psi\tau} / V_E \quad \text{in } S_{DET} \tag{19}$$

which should be satisfied not on the unknown part of the domain (outside of the blade) S_{CAV}, but on a simplified sufficiently stretched downstream (to embody the calculated cavity) and located outside of the blade domain S_{DET} (see Fig. 12). Note that the condition (19) possesses a universality, it is valid both for the points lying on the boundary of the cavity, and the points lying outside of the cavity, because the pressure outside of the boundaries of the cavity for natural cavitation in weightless fluid should necessarily be larger than in the cavity and upon its boundaries.

It should be noted that when replacing the condition (15) by a set of requirements (18) and (19) a multitude of admissible solutions of the considered problem widens considerably and becomes indefinite.

Thirdly, outside of the blade for the open cavity closure model it follows rigorously from the known property of stationary cavities in weightless fluid, namely from the property of convexity of the cavity [52]

$$q \geq 0 \quad \text{in } S_{DET} \tag{20}$$

Fourthly, behavior of the given function and sought for function in the vicinity of the sharp leading edge is regulated a

$$\begin{aligned} &\lim_{\xi \to \xi_0} \left[q(\xi; \bar{r}) \cdot (\xi - \xi_0)^{1/4} \right] = \\ &- \lim_{\xi \to \xi_0} \left[\gamma(\xi; \bar{r}) \cdot (\xi - \xi_0)^{1/4} \right] \neq \infty \end{aligned} \tag{21}$$

The latter requirement coincides with the traditional formulation of the problem and is further on used when linearizing functional of the artificial variational problem.

It is clear from comparison of the presented traditional and nontraditional formulations of the problem A, that, because of widening set of solutions when passing over from equality to inequality in the dynamic boundary condition, as indicated, the set of admissible solutions becomes infinite. With the goal of obtaining a single unique solution on the basis of nontraditional formulation, require a minimization of the artificial functional F over the multitude of solutions, satisfying the conditions (18)-(21). In this case the functional is adopted in the following form

$$F = \int_{S_B \cup S_{DET}} (W_\tau^+ / V_E + \sigma / 2 + V_{\psi\tau} / V_E) \, q \, ds \tag{22}$$

It is not difficult to check that, according to the conditions (18),(19),(20), the integrand equals zero in the domain S_B and both multiplyers under the integral sign are nonnegative in the domain S_{DET}, and,consequently, minF=0. Not complicated considerations show that the indicated minimal (zero) magnitude of the functional F is reached exactly on that very solution of the problem A which corresponds to the traditional formulation.

In fact the functional will differ from zero in the case, when there exists within S_{DET} an area element for which both multipliers in the integrand would be positive simultaneously. Exactly this can take place if on this area element there is simultaneously a simple layer and the pressure is higher than that in the cavity. The latter does not correspond to the traditional solution, for which outside of the cavity (on the surface of which the pressure is minimal and constant) sinks and sources should be absent. But if F equals to zero, there are no such area elements in the area under control, and, consequently, the obtained solution corresponds to the traditional approach.

Thus, the described artificial variational formulation of the problem A is equivalent to the traditional one, presented earlier. It should be noted however that the artificial functional is not linear. Perform some transformations with the aim to obtain its linear form. With account of the previous relationships

$$F = \int_{S_B \cup S_{DET}} (W_{q\tau} / V_E + W_{\gamma\tau} / V_E - \gamma_r /(2V_E) + \sigma / 2 + V_{\psi\tau} / V_E) \, q \, dS \tag{23}$$

One term can be eliminated, accounting for the equation

$$\int_{S_B \cup S_{DET}} (W_{q\tau} / V_E) \, q \, dS = 0 \tag{24}$$

which can be proved by a interchanging the order of integration in the corresponding integral. It is important to have in mind, that the leading edge is assumed to be sharp (which is regulated by the condition (21)) and the suction force is not realized on it. Eventually one derives a complete linear form of the functional

$$F = \int_{S_B \cup S_{DET}} [W_{\gamma\tau} / V_E - \gamma_r /(2V_E) + \sigma / 2 + V_{\psi\tau} / V_E] \, q \, dS \tag{25}$$

When stating a linearity, it is taken into account, that the intensity of the attached vortices γ_r is assumed to be prescribed within the blade, i.e. on S_B, and, therefore, all terms in the square brackets are given functions or can be calculated through them. The linear form of the functional allows (after discretization) to reduce the numerical solution of the problem A in its artificial variational formulation to the problem of linear programming.

In 1985 there was carried out with use of the simplex method of linear programming a numerical solution of the described problem A for a concrete supercavitating screw propeller [48], [49]. The model of the designed propeller was manufactured of silumin alloy, had a diameter 0.2 m (see Fig. 14) and was tested first in the cavitation tunnel of the KSRI, and then in the cavitation tunnel of the Gdansk Institute. Some of the input data, the results of the calculation and results of the experiment are given in the Table 5 and in the Fig. 15-18.

Table 5. The input data (first 5 lines) and the results of the verification calculation (problem A) of the supercavitating propeller N8401($Z=3$; $A_E/A_0=0.92$; $J=1.0$; $\chi=0.25$; $K_T=0.084$)

$\bar{r}$	0.265	0.404	0.595	0.786	0.925
c/R (preset)	1.045	1.245	1.416	1.355	0.939
δ (preset)	0.087	0.060	0.037	0.027	0.030
$\bar{\Gamma}$ (preset)	0.0145	0.0187	0.0213	0.0195	0.0129
C_L (preset)	0.1340	0.1170	0.0892	0.0680	0.0562
σ (preset)	0.1479	0.0957	0.0556	0.0352	0.0265
P/D (calcul.)	1.69	1.37	1.28	1.28	1.26
δ_P (calcul.)	-0.0007	0.0073	0.0124	0.0141	0.0124
L_{CAV}/c (calcul.)	1.000	1.000	1.080	1.160	1.000
$e_{CAV}(L)/c$ (calcul.)	0.282	0.140	0.076	0.084	0.069
$e_{CAV}(1)/c$ (calcul.)	0.282	0.140	0.074	0.075	0.058
$e_{CAV}(1)/c$ (exper.)	-	-	0.080	0.081	-

Comment: c - blade section chord length, R - propeller radius, δ -maximum blade section thickness-chord length ratio, $\bar{\Gamma}$ - non-dimensional circulation around blade section, C_L - lift coefficient, σ - local cavitation number, P/D - blade section pitch ratio, δ_P - maximum camber of blade presser surface, L_{CAV}/c - cavity length at some blade section- chord length ratio, $e_{CAV}(L)/c$ cavity thickness at a cavity termination point for given blade section-chord length ratio, $e_{CAV}(1)/c$ - cavity thickness at a blade section enter edge- chord length ratio.

Note additionally that the propeller reached its design regime. The experimental thrust coefficient was 0.0844 for a given magnitude 0.0840, the efficiency in the test was 0.543, i.e. 4% more than that obtained by calculations. A good correlation in forces confirmed a viability of the approximate correction, accounting for the loss of the part of the contour of integration when determining the circulation in a given cylindrical section of the blade, related to the presence of cavities in the inter-blade space. It is to be noted here that in the adopted cavity closure model, the supercavity terminates for a given cylindrical section in its widest cross-section and, further on there recedes to the infinity a helical-type stripe of the wake of constant width (measured along the cylinder surface), equal to the maximal thickness of the cavity. As the cavity thickness is unknown in advance the interaction process is envisaged within the problem solution algorithm to account for the indicated approximate correction (two steps appear to be sufficient). In the presented calculation the final correction resulted in the 18,6% reduction of the thrust compared to a purely linear approach.

The maximum difficulties when testing were connected with manufacturing of sharp leading edges, which (if of insufficient strength) could deform during the tests of the model in the cavitation tunnel. Therefore, when prescribing the loading there was secured a sufficient magnitude of the multiplier of the leading edge singularity. When manufacturing the model, in the vicinity of the leading edge the whole calculated gap between the cavity surface and the pressure side of the blade was filled by certain material. The thickness distribution of the remaining part of the section had a segment profiling (see Fig. 15). The law of the distribution of the circulation along the radius was assumed optimal, and found in the frame of the lifting line theory with use of the generalized optimality conditions obtained by Achkinadze in 1989 [42], [53], [54] and allowing to account for the radius-wise distribution of the cavitation drag of the blade.

Chord-wise distribution laws assumed close to a uniform one with a certain increase of the loading in the vicinity of the leading edge. In the process of the tests of the model in the cavitation tunnel there were made (except the force tests) drawings of the development of the cavity planform and thickness measurements at the cavity training edge. The correlation with the cavity planform calculations (see Fig, 16) and in the distribution of the cavity thickness along radius (see Fig. 15, Fig. 16, Fig. 17 and Table 5) at a design advance coefficient, equal to 1.0, and at a design cavitation number, equal to 0.25, turned out to be satisfactory. However, because of the thickening of the leading edge up to the calculated boundaries of the cavity (to the extent of 10% of the chord from the leading edge). At the design regime the cavity started not at the leading edge but 5-10% of the chord further downstream. This entails the following: at the design advance coefficient the whole (excepting the aforementioned region at the leading edge) suction side was covered by a dense bubbly cavitation, whereas the film-type cavity formed at a somewhat smaller (5% less) advance coefficients. There is a certain hope that, in the full-size situation the bubble cavitation would be replaced by a film-type one. The pressure side at a design advance ratio (J=1.0) was completely free of cavitation (see Fig. 18).

Later in Gdansk under guidance of Professor Szantyr and Dr. I.J.Dudziak were conducted the tests of this model of the supercavitating propeller in the conditions of oblique flow for axial cavitation number of 0.4, which is noticeably higher than the design one 0.25. However, for this out-of-design regime in the oblique flow the pressure surface was free of cavitation, which is an evidence of the sufficient reserve for avoidance of the cavitation occurrence on the pressure side within the considered project.

The efficiency of the tested screw propeller turned out (as foreseen by the calculations) close (a bit larger) to the efficiency of the propeller of "CK" series, although the section thickness of the designed propeller was taken noticeably larger (more exactly, the maximum blade section thickness-chord ratio was larger than that for the "CK" propeller series 16, 33 and 50 % for the sections corresponding to the relative radia 0.6, 0.8 0.95 correspondingly. Besides, near the leading edge the thickness was in fact larger for all cross-sections, located at the relative radia less than 0.8).

Further development of the described theoretical investigation was directed to obtaining such a form of the artificial functional, which coincides with the approximate (within lifting line theory) expression of the profile losses of the screw propeller due to just cavitation drag of the blades. Such a functional, as shown in the dissertation of Achkinadze [53](1993), has the following simple form

$$F_1 = \int_{S_B \cup S_{DET}} (\sigma / 2)\, q \sin\beta \, dS \tag{26}$$

This functional is linear and should be minimized, although it no longer has a zero value. In obtaining such a form of the functional a number of assumptions were made. With the goal of evaluating the error introduced by these assumptions numerical solution of the problem A was obtained for the supercavitating propeller, described above. Comparison with the results, obtained with use of a completely rigorous form of the functional (25), showed an insignificant divergence in the obtained form of the cavity and the pressure side of the blade in the two compared cases.

The latter enables to pass over to the solution of the problem of the design calculation in a more complete (than for problem A) formulation, i.e. with account of restrictions on the thickness and length of the cavity, of the reserve of the cavitation avoidance on the pressure side etc., for given distribution of circulation along the radius (this distribution can be either prescribed arbitrarily or adopted optimal, as earlier with the utilization of the generalized optimum condition in the frame of the lifting line theory [42]).

Besides the geometry of the cavity in the considered case of a more complete formulation one can obtain optimal distribution of the attached vortex layer in the chordwise direction and a corresponding form of the pressure surface with use of the numerical method of linear programming. With such optimization the induced losses and friction losses remain unchanged and the profile losses, stipulated by the cavity drag, are minimized. The latter circumstance enables one to treat use of the functional in form (26) as an application of a certain variational principle (the principle of minimum cavitation drag), having a physical sense of minimization of cavitation drag of the blade sections of the supercavitating propeller under design. The latter is valid at least for each section separately, which can be easily seen taking into attention the expression for the cavitation drag of the two-dimensional foil in the case of use of the open closure model of the cavity, namely

$$C_{DCAV} = \sigma \, e_{CAV}(L) \tag{27}$$

where $e_{CAV}(L)$ - is cavity thickness at a termination point related to the chord (for open model this is the largest magnitude of the cavity thickness), i.e. where terminates the simple layer modeling the cavity.

With use of the indicated more complete formulation were conducted design calculations of a systematic series of the optimal 3-blade supercavitating screw propellers with segment profiling. For practical use the results of this series were processed in form of the corrections for the influence of the lifting surface for supercavitating screw propellers [50], similarly to how it had been done previously for the noncavitating propellers. Given in Fig.19 is a (borrowed from the indicated work) comparison of the correction for the curvature of the mean line of the body "blade-cavity" for cylindrical sections of the supercavitating propellers with analogous correction for the mean line of cylindrical section of noncavitating screw propeller. It can be seen that for the supercavitating screw propeller the considered corrections depend on the cavitation number.

Considering concrete magnitudes, e.g. at a relative radius of 0.79, one sees that for the propeller of expanded area ratio 0.475 the curvature correction slightly exceeds the analogous one for noncavitating screw propeller. For the propellers of expanded area ratio 0.950 there exists a much bigger difference with the same trend. The value of corrections for noncavitating propellers are designated in Fig.19. by horizontal dashed lines separately for two expanded area ratios.

It seems that upon the augmentation of the cavitation number (for the same thrust coefficient) the magnitude of the corrections for the supercavitating propellers should tend to the magnitude of the analogous corrections for the noncavitating propellers, but this is not so. The explanation consists in that for an optimal supercavitating propeller required are sufficient thickness and length of the cavity. But, with growth of the cavitation number this requirement is more difficult to fulfill and the optimal pitch and curvature values grow. For reasonable magnitudes of cavitation number (for the designed propeller N8401 the ratio of the axial cavitation number to the thrust coefficient, not corrected for nonlinearity, equals 2.5) the corrections for curvature for the cavitating and noncavitating propellers for a expanded area ratio 0.475 differ insignificantly (less than 20%), which is indicative of a possibility to consider the blade and the cavity as a single lifting body in a flow of inviscid fluid. The latter possibility was contested by some specialists (Panchenkov).

When using the methods of optimization, such e.g. as a linear programming, there arises a need in smoothing the form of the pressure surface and even its artificial simplification, because, as a result of the design calculation with optimization, it can become excessively complicated, and the influence of this complication upon the efficiency of the propeller would be negligibly small. Achkinadze in 1974 [51] applied a principle of the minimum of cavitation drag to solve a two-dimensional problem of an optimal supercavitating section. He found that form the practical viewpoint it is sufficient to limit oneself to simple forms of the pressure surface, but one should (accurately enough) account for restrictions for the thickness and length of the cavity. Some examples of such calculations were published in [27].

Special attention deserves a proper choice of the optimal lift coefficient with account of the conditions, ensuring sufficient thickness of the cavity, as well with account of the friction drag C_f on the pressure side. For example, this problem was solved for a thin 2-dimensional arc at zero cavitation number. In particular, the following values were obtained for the optimal lift coefficient, angle of attack and curvature of the pressure side [27]

$$C_{LOPT} = 2.548\sqrt{C_f}\,; \quad \alpha_{OPT} = 0.1838\, C_{LOPT}\,; \qquad \delta_p = 0.1294\, C_{LOPT}$$

The approach described above is linear. As it becomes obvious in the course of time, the employed linear approach does not adequately allow to evaluate the effect of real (non sharp) leading edge. Recent developments in the field of optimal supercavitating profiles are connected with use of nonlinear approach and investigation of the influence of a spoiler, wedge-type leading edge and other nonlinearities [26].

Note an important circumstance, occurring in use of the improved propeller profiles. Improvement of hydrodynamic fineness of the section, measured by a relative variation (decrease) of the inverse fineness $\Delta\varepsilon/\varepsilon$, leads to the growth of efficiency of the supercavitating propeller by a quantity, which can be approximately estimated by means of a simple formula [53]

$$\Delta\eta_0/\eta_0 = -2\varepsilon\ (\Delta\varepsilon/\varepsilon) \qquad (28)$$

if the inverse finenes is taken for the section at relative radius 0.7.

It follows straitforwardly from (28), that relative improvement of hydrodynamic fineness of the profile gives a relative improvement of the design of the propeller which K/2 less efficient (where K=1/ε -hydrodynamic fineness of the supercavitating profile). For a hydrodynamic fineness of about 20 there takes place a 10 times reduction of the relative gain when passing from a profile to the propeller. Although the increase of the propeller efficiency is expensive, the increase of the efficiency of the supercavitating propeller by means of optimization of the profiles requires an improvement of their hydrodynamic fineness of not less than 10%, to obtain only a one percent growth in efficiency.

Conclusion

In conclusion, the author would like to express a hope that the experience in research and development in the field of he supercavitating screw propellers and similar propulsors, partly reflected in the presented lecture, would be called for and would be useful for the future. The author would also like to express his gratitude to his teachers: Professors V.M.Lavrientiev, V.V.Rozhdestvensky and A.A.Russetskiy, and to thank Professor J.A.Szantyr and Dr.I.J.Dudziak from Poland for the tests he had conducted in the cavitation tunnel of the SC propeller designed by the author.

References

1.Tulin M.P. 2000 Fifty years of supercavitating flow research in the U.S.: personal recollection. Applied hydromechanics, National Academy of Sciences of Ukraine Institute of Hydromechanics, Vol.2, Num.3, pp.100-107 (in Russian).

2.Burill W.C. 1951 Sir Charles Parsons and Cavitation. Transactions of the Institute of Marine Engineers, Vol.LXIII, No.8.

3.Springorum K. 1932 Hydromechanische Probleme des Schiffsantriebs, Hamburg, (p.331).

4.Jessup S.D., Wang H.-C. 1997 Propeller design and evaluation for a high speed patrol boat incorporating iterative analysis with panel method. Tr. P/S'97 Symposium, Sept. 23-24, Virginia Beach, USA, pp.11/1-20.

5.Georgievskaya E.P., Mavlyudov M.A., Hadjimikhalev V., Kozhukharov P. 1989 A new generation of cavitating propellers and their practical application to "Kometa" hydrofoil. Proc 4-th Internat. Symposium on PRADS-1989, Varna, Bulgaria, Vol.3, pp.123/ 1-11.

6.Kinnas S.A. 1996 An international consortium on high-speed propulsion. Marine Technology, Vol.33, No.3, pp.203-210.

7.Pozdunine V.L. 1941 Problems of ship propellers. Soviet Science, No.2.

8.Pozdunine V.L. 1944 On the working of supercavitating screw propellers. Tr. of INA, Vol.86.

9.Pozdunine V.L. 1944 On the working of supercavitating screw propellers. Doklady AN SSSR, Vol. XXXIX, №8, cc. 334-339.(in Russian)

10.Pozdunine V.L. 1947 The effectiveness of supercavitating propellers. Izvestia OTN AN SSSR, No.10. (in Russian)

11.Georgievskaya E.P. 1978 Screw propellers cavitation erosion. Leningrad "Sudostroenie Publ. House" 206 p.(in Russian)

12.Tachmindji A.J., Morgan W.B. 1958 The design and estimated performance of a series of supercavitating propellers. Proc. of the Second ONR Symposium on Naval Hydrodynamics, U.S., August.

13.Caster E.B. 1963 TMB 2,3 and 4-bladed supercavitating propeller series. DTMB Report 1637, January.

14.Tulin M.P., Burkart M.P. 1955 Linearized theory for flows about lifting foils at zero cavitation number. DTMB Report C-638, Feb.

15.Rosen G. High speed propellers. ISP, Vol.16, No.176, pp.110-116.

16.Davis B.V., English J.W. 1968 The evolution of a fully cavitating propeller for a high-speed hydrofoil ship. Proc. of the 7-th ONR symposium on naval hydrodynamics, Rome, August.

17.Mavlydov M.A., Rousetsky A.A., SadovnikovY.M., Fisher E.A. 1973 Propulsors for high speed ships. Leningrad "Sudostroenie Publ. House" 240 p.(in Russian)

18.Mavlydov M.A., Rousetsky A.A., SadovnikovY.M., Fisher E.A. 1982 Propulsors for high speed ships. Second revised and enlarged edition, Leningrad "Sudostroenie Publ. House" 280 p.(in Russian)

19.Ship Theory Handbook 1985 Ed. by Y.I.Voitkounski, Vol.3, Leningrad "Sudostroenie Publ. House" 540 p.(in Russian)

20.Ikonnikov V.V., Maskalik A.I. 1987 Unique feature of hydrofoil ships design and formation. Leningrad "Sudostroenie Publ. House" 318 p.(in Russian).

21.Rousetsky A.A. 2000 Alar ships (Крылатые корабли). Maritime Journal (Морской жупнал), "Sudostroenie Publ. House", pp. 46-49, N2 (in Russian)

22.Prishchemikhin Yu. N. 1969 Cavitation tank with remote testing operation. Tr. of the 12th ITTC, September.

23.Van Manen J.D. 1971 The effect of cavitation on the interaction between propeller and ship's hull. Proc. of the IUTAM Symposium, June 22-26, Leningrad, pp.305-328, "NAUKA", Chief Office PML, M., 1973.

24.Fisher E.A. 1966 Experemental determination of the screw propeller cavitation size. Tr. KSRI, Vol.231.(in Russian)

25.Achkinadze A.S., Fridman G.M 2000 Optimal profiles for supercavitating propeller screws with spoilers and fixed angle of frontal edge taper. Applied hydromechanics, Institute of Hydromechanics of NAS of Ukraine, volume 2 (74), number 3, pp.5-16 (in Russian).

26.Achkinadze A.S., Fridman G.M 2000 Optimal Sections for Supercavitating Propellers with Spoiler and Preset Leading Edge Angle. Proc. NCT'50 International Conference on Propeller Cavitation, 3-5 April, University of Newcastle, Newcastle upon Tyne, United Kingdom, pp. 263-274.

27.Achkinadze A.S., Fridman G.M 1995 On some aspects of design of supercavitating foils and propellers. Variation and asymptotic approach. Proc. An international conference on propeller cavitation to celebrate 100 years of propeller cavitation research (PROPCAV'95), 16-18 May, Newcastle upon Tyne, United Kingdom, p.163-174.

28.Rozhdestvensky K.V., Fridman G.M. 1991 Matched asymptotics for free surface lifting flows with spoilers. In book: Matched Asymptotics in hydrodynamics, SIAM.-Edited by T.Miloh, Philadelphia, pp.499-517.

29.Zaitsev N.A., Maskalik A.I. 1967 Fatherland hydrofoils. Second revised and enlarged edition, Leningrad "Sudostroenie Publ. House" 364 p.(in Russian)

30.Basin A.M., Goshev G.A. 1963 Experimental investigation of the semi-submerged propellers characters. Tr. of LIWT, Vol. X.

31.Baeva M.A., Mizina M.Y., Sadovnikov Y.M. 1981 Hydrodynamics characters of the cavitation profile with spoiler. Transactions of the Academician A.N.Krylov Scientific and Technical Shipbuilding Society, 1981, vol.358, p.44-60 (in Russian).

32.Rose J.C. 1993 Combination surface propeller and water jet systems. Pr. of the 3rd International Design Symposium on Yacht and Small Craft Design, Chianciano Terme, Italy.

33.Ibragimova T.B., Mavlydov M.A., Rousetsky A.A. 1995 Basic principles of propulsor efficiency comparisons. Pr. Third International Conference on Fast Sea Transportation.

34.McMahon J.F., Dai C.M., Gowing S., Lin G., Peterson F.P. 2000 Ventilated Waterjets for high speed ships. Proc.: SNAME Symposium "Propellers/Shafting'97", 20-21 September 2000, Virginia Beach, USA. pp.11/1-11/9.

35.Rose J.C., Kruppa C.F.L. 1991 Surface piercing propellers - methodical series model test results. Proc. of FAST'91, Trondheim, June.

36.Toyoda M., Kato H.,Yamaguchi H. 1999 Study on theoretical design method of trans-cavitating propeller. Journal of the SNA of Japan, Vol. 186, pp.41-49. (in Japan)

37.Ukon Y., Kudo T., Fujisawa J., Matsuda N. 1999 Experimental evaluation of trans-cavitating propellers. Journal of the SNA of Japan, Vol. 186, pp.51-58. (in Japan)

38.Kozhukharov P., Zlatev Z. 1983 Cavitating propeller characteristics and their use in propeller design. Proc. High-speed surface craft conference, London, May.

39.Kozhukharov P. 1983 Investigation and design on cavitating screw propellers operating in oblique flow. Ph. D. thesis, Leningrad, LKI (SMTU).

40.Newton R.N., Rader H.P. 1961 Performance data of propellers for high-speed craft. Tr. RINA, Vol.103.

41.Gawn R., Burrill L.C. 1957 Effect of cavitation on the performance of a series of 16 in. model propellers. Tr. INA, Vol.99, pp. 690-728.

42.Achkinadze A.S. 1989 Design of optimal screw propellers, turbines and freely rotating turbopropellers adapted for radially nonuniform swirled flow. Proc. Fourth Internat. Symposium on PRADS'89, 23-28 Oct. 1989, BSHC, Varna, Bulgaria, Vol. 3, p. 124/1-13 (in English).

43.Achkinadze A.S., Krasilnikov V.I., Stepanov I.E. 2000 A Hydrodynamic Design Procedure for Multi-Stage Blade-Row Propulsors Using Generalized Linear Model of the Vortex Wake. Proc.: SNAME Symposium "Propellers/Shafting'97", 20-21 September, Virginia Beach, USA. pp.20/1-20/21, (in English)

44.Fabula A.G. 1962 Thin-airfoil theory applied to hydrofoils with a single finite cavity and arbitrary free-streamline detachment. JFM, Vol.12, Part 2.

45.Geurst J.A. 1956 Linearized theory for partially cavitated hydrofoils. ISP, Vol.6, No.60, pp. 369-384.

46.Kinnas S.A., Kosal E.M. Young J. 1999 Computational techniques for the design and analysis of super-cavitating propellers. Pr. FAST'99, 31 August-2 September, Seattle, WA, USA.

47.Achkinadze A.S. 1983 Application of mathematical programming methods in the linear theory of cavity flows. Proc. 12th ses. SMSSH, BSHC, Varna, Bulgaria, 19-23 Sept., vol. 2, p. 32/1-19 (in Russian).

48.Achkinadze A.S., Narvsky A.S. 1985 Supercavitating propeller design equation in lifting surface theory and method of its solution. Proc. 14th ses. SMSSH, BSHC, Varna, Bulgaria, 23-29 Sept., vol. 1, p. 19/1-21.

49.Achkinadze A.S., Narvsky A.S. 1987 Calculation of cavitating propellers based on the lifting-surface theory. Proc. 4th Internat. congress IMAEM, BSHC, Varna, Bulgaria, 25-30 May, vol. 5, p. 158/1-15.

50.Achkinadze A.S., Narvsky A.S. 1989 Supercavitating propeller lifting-surface corrections. Proc. 18th ses. SMSSH, BSHC, Varna, Bulgaria, 25-30 Sept., vol. 1, p. 19/1-4.

51.Achkinadze A.S. 1974 Linear problem of supercavitating wing and problem of optimal wing's shape (variation approach). Transactions of the Academician A.N.Krylov Scientific and Technical Shipbuilding Society, Vol. 217, p.139-164 (in Russian).

52.Rozhdestvensky V.V. 1977 Cavitation. Textbook, Leningrad "Sudostroenie Publ. House", 247 p.

53.Achkinadze A.S. 1993 Design calculation of noncavitating and highly cavitating propellers with used vortex theory with take into acount load and radially nonuniform inflow. Thesis of Dr.I., Saint Petersburg State Marine Technical University, Saint Petersburg, Russia.

54.Achkinadze A.S., Krasilnikov V.I. 1997 A generalized optimum condition for wake adapted screw propellers. Proc.: SNAME Symposium "Propellers/Shafting'97", 23-24 September, Virginia Beach, USA. p.22/1-22/28.

55.Egorov I.T., Sadovnikov Y.M., Isaev I.I., Basin M.A. 1971 Artificial cavitation., Leningrad "Sudostroenie Publ. House" 280 p.(in Russian).

56.Kruppa C 1972 Testing of partially submerged propellers. 13th ITTC, Report of cavitation committee, Apendix V.

57.Claus F.L. Kruppa 1969 High speed propellers hydrodynamics and design. Textbook No.035, The Department of Naval Architecture and Marine Engineering, The University of Michigan College of Engineering, September, 78 p.

58.Comstock J.P., editor 1967 Principles of Naval Architecture. Published by SNAME, New York, p.827.

59.Etter R.J. 2000 State of the art - cavitation test facilities and experimental methods. NCT'50 International Conference on Propeller Cavitation, 3-5 April, University of Newcastle, Newcastle upon Tyne, United Kingdom.

Figures

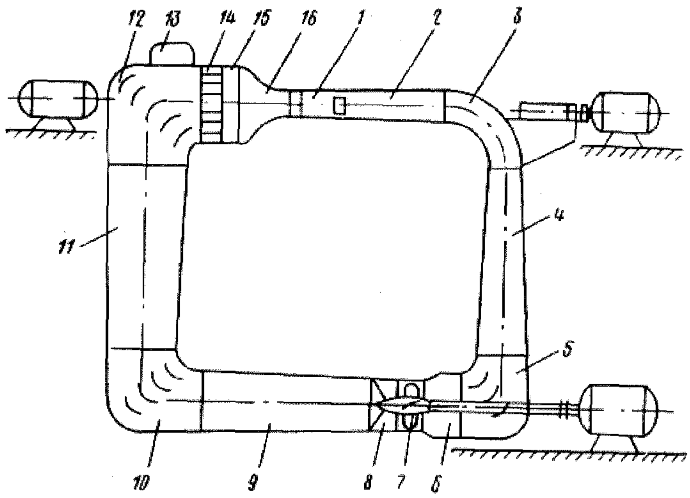

Fig.1. Cavitation tunnel

1.Working section
7.Impeller
8.Aline device
13.Variable pressure shaft
14.Honeycomb rectifier

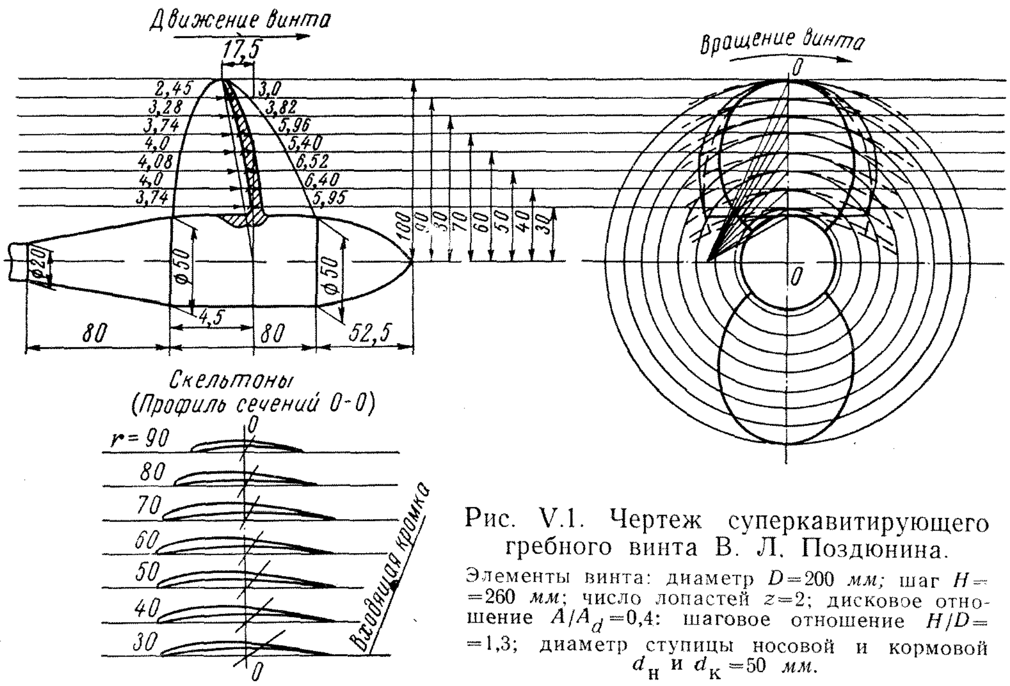

Fig.2.Posdunine's supercavitating propeller drawing [55]
(D=0.2m., p=0.26m., A_E/A_0=0.4)

Fig.3.Propeller operating on supercavitating regime [16]

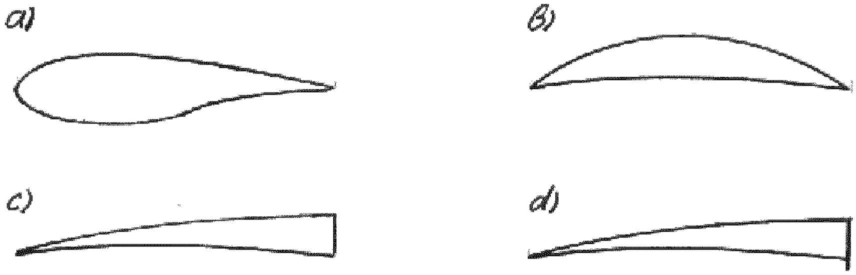

Fig.4.Blade section types

a)conventional

b)segment

c)wedge-shaped (supercavitating)

d)wedge-shaped with a spoiler (supercavitating with a spoiler)

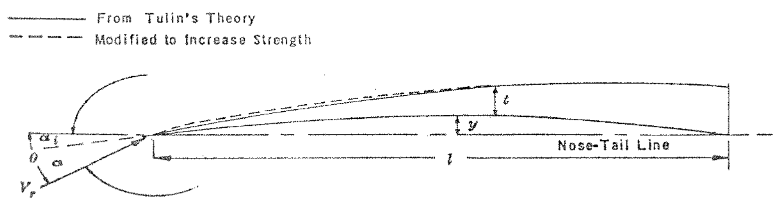

Fig.5.Tulin's patented two parameters supercavitating section

(C_L=0.2, α=2 degrees) [12]

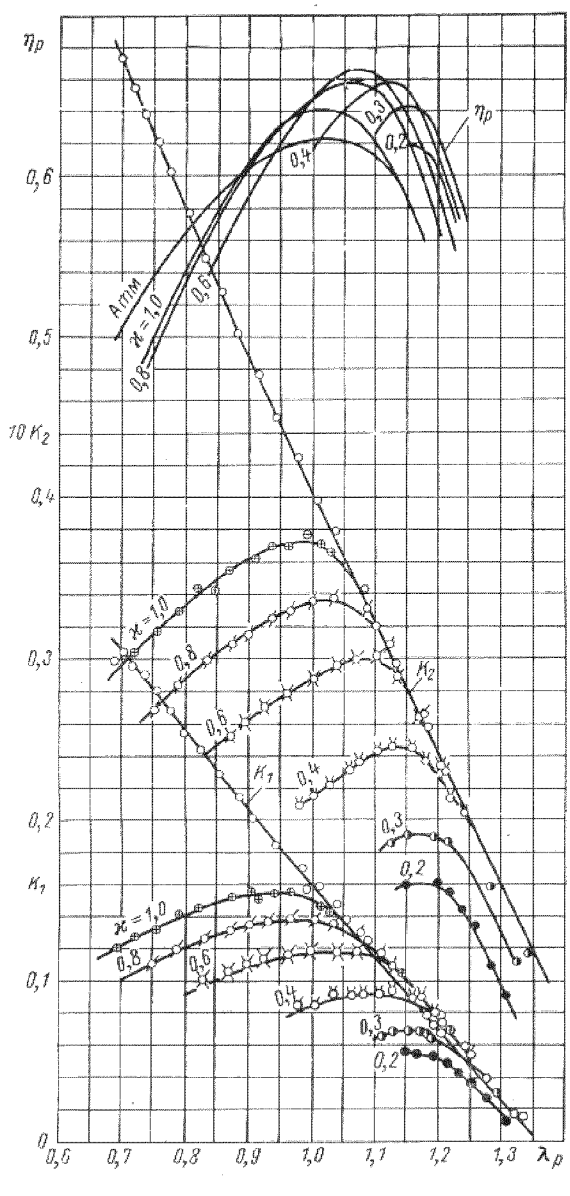

Fig.6. Characteristic curves for propeller of series "K" (z=3; A_E/A_0=0.81; P/D=1.4; wedge-shaped section type) [55]

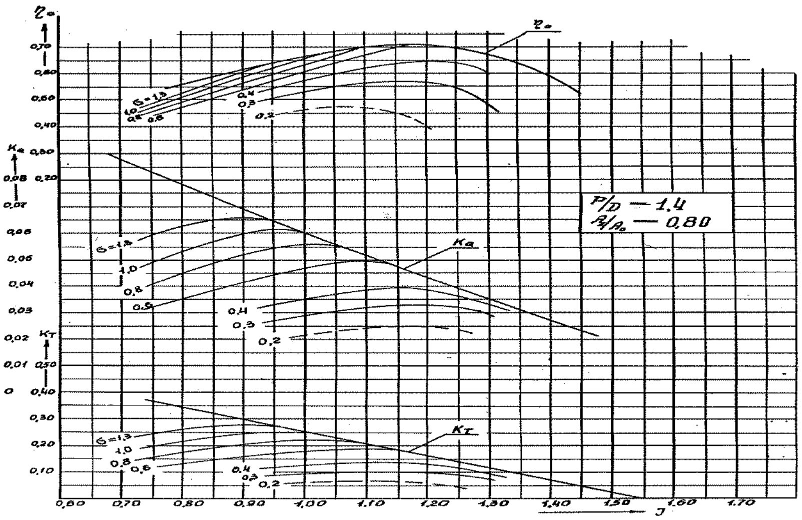

Fig.7. Characteristic curves for propeller of series "CK"
(z=3; A_E/A_0=0.80; P/D=1.4; segment section type) [18]

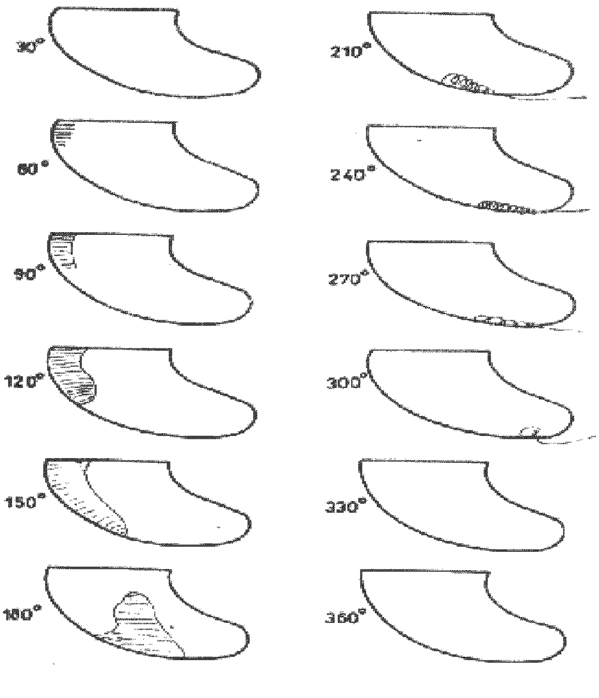

Fig.8.Face residual cavitation development at various blade phase angle in oblique flow 16 degrees (χ=0.65, J=1.0) [5]

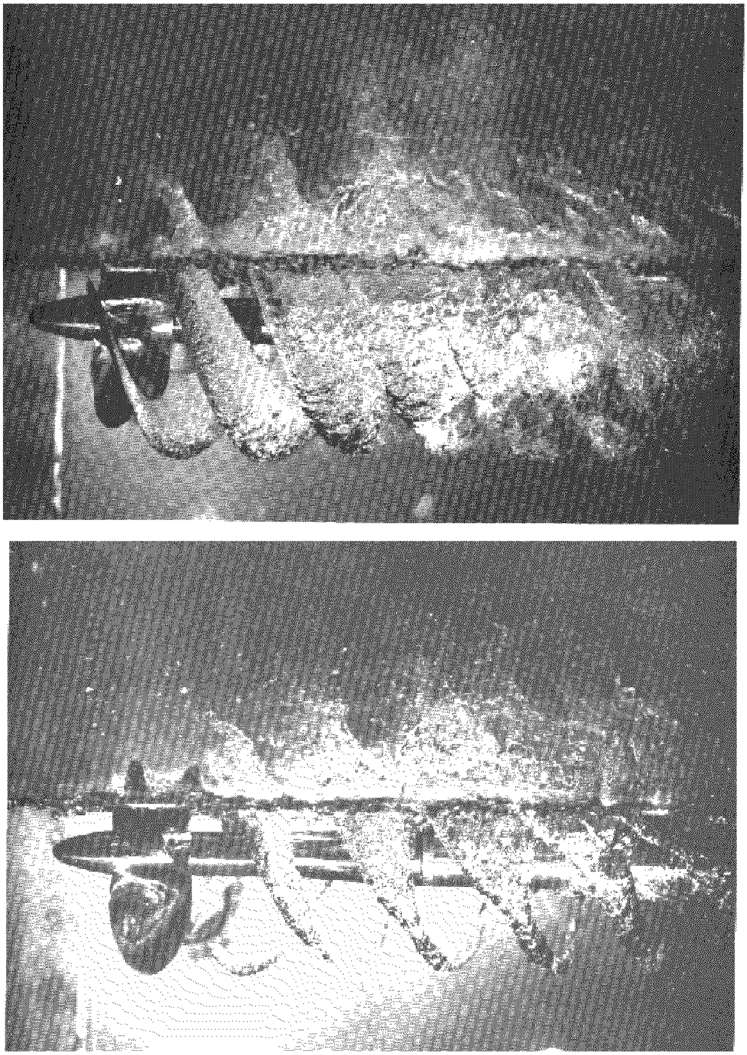

Fig.9.Surface piecing propellers in working regime.
(J=1.1 and 0.9; immersion 0.7D) [56]

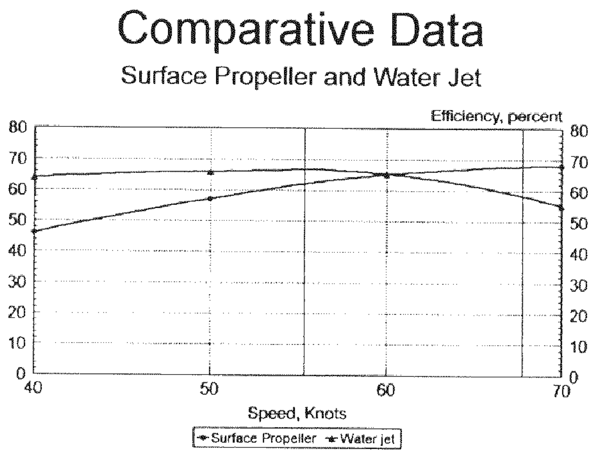

Fig.10.Efficiency versus ship speed (comparative data of SPP and water jet) [32]

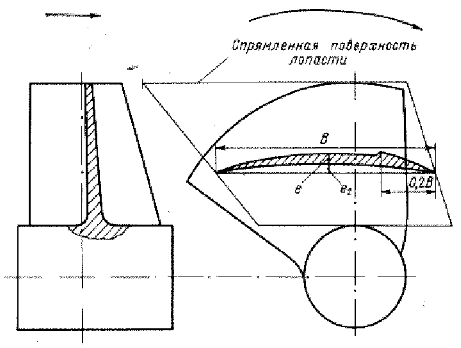

Fig.11.Blade geometry drawing of ventilated waterjet impeller blade [18]

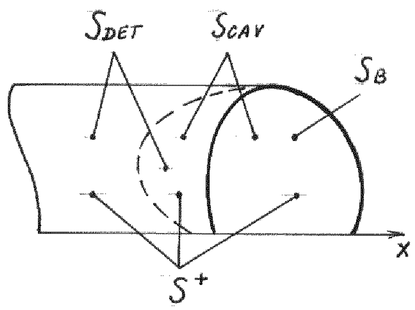

Fig.12. Domain nomenclature

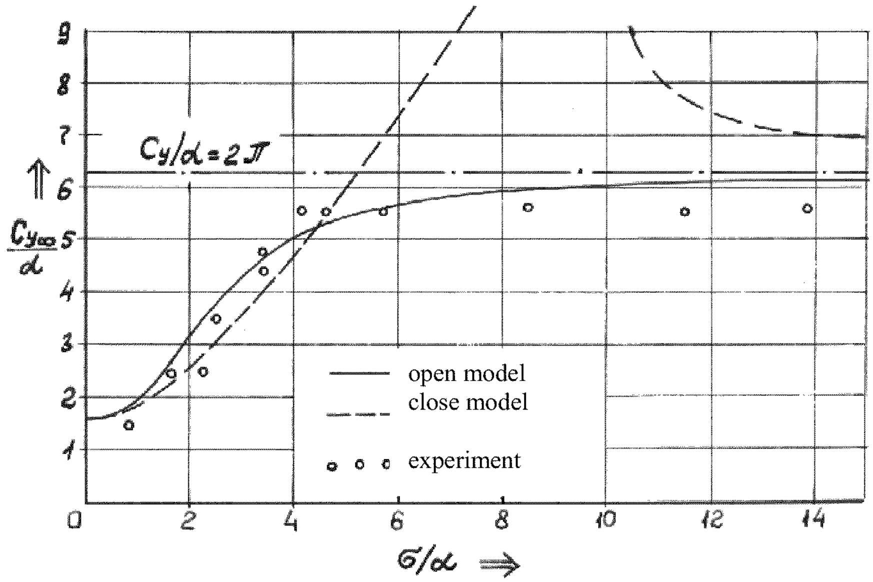

Fig.13.Lift coefficient-angle of attack ratio versus local cavitation number-angle of attack ratio for the supercavitating flat plate (comparative data of open and close cavitation models)

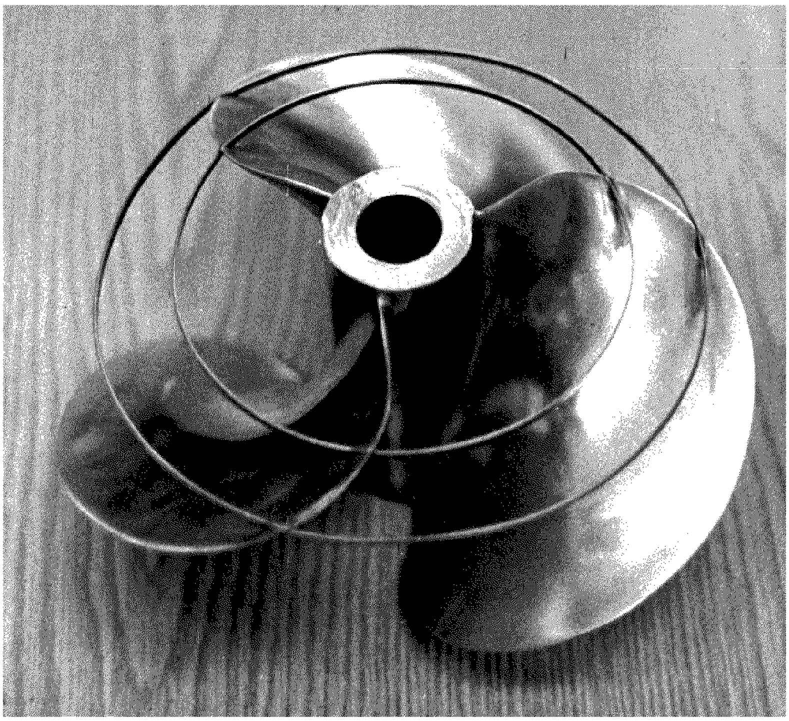

Fig.14.Designed in LSI supercavitating propeller model N8401 with cavity thickness measurer rings (z=3; A_E/A_0=0.92; P/D(0.6)=1.28; χ=0.25; J=1.0; K_T=0.084; segment section type)

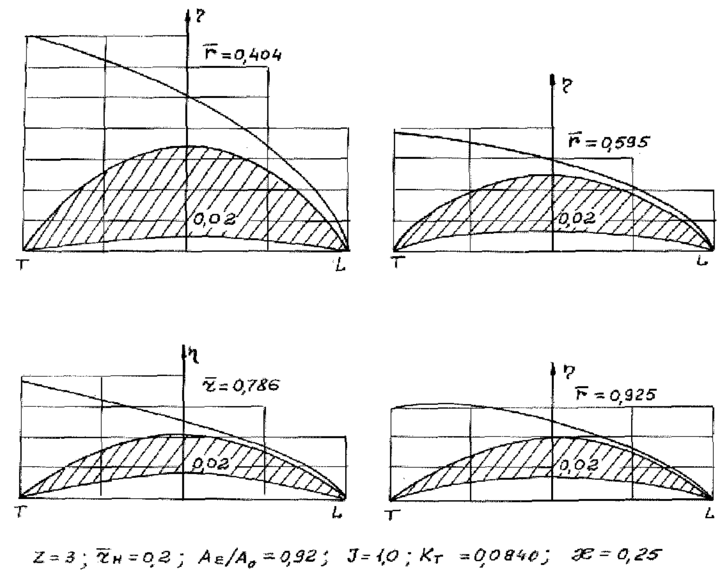

Fig.15.Cavity boundary and pressure surface calculation ordinates (multiply on 6.25) for supercavitating propeller N8401 at design regime [49]

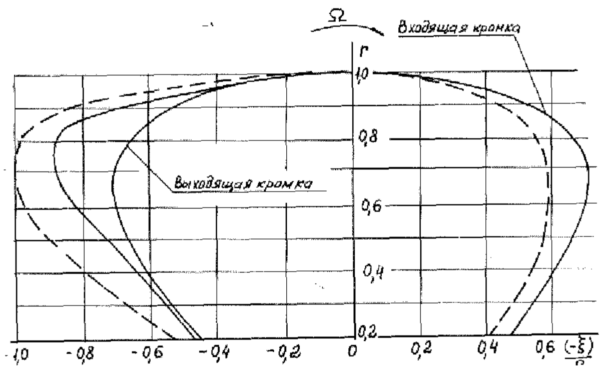

Fig.16.Cavity configuration for supercavitating propeller N8401 at design regime in sucking surface [49]

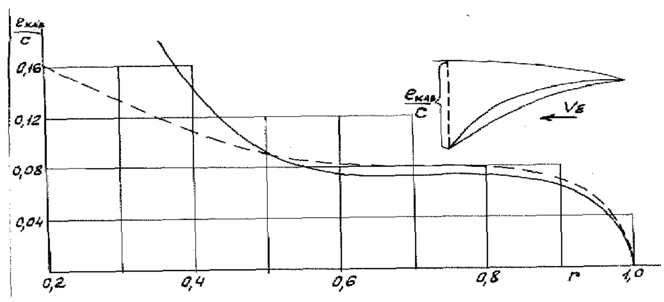

Fig.17.Radial cavity thickness distribution at blade trailing edge for supercavitating propeller N8401 at design regime [49]

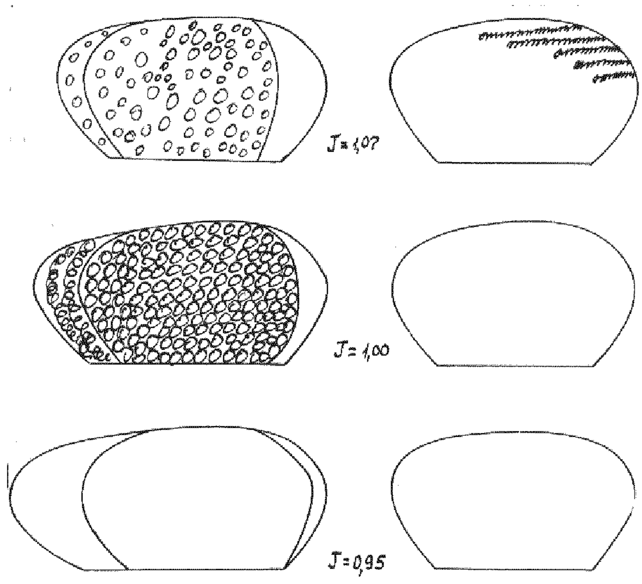

Fig.18. Blade surface cavitation development at various advance ratio for supercavitating propeller N8401 (pressure surface is on the right) [49]

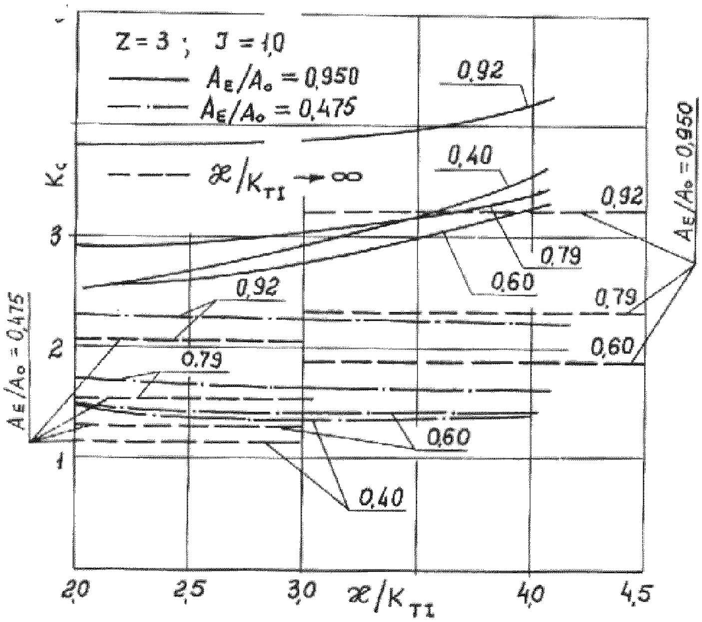

Fig.19.Correction for the camber of the blade cylindrical section central line together with the cavity (comparative data of supercavitating and non-cavitating propellers) [50]